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A platform for assessment of energy recovery technologies by pressure reduction in water distribution networks

Dissertação para obtenção do Grau de Mestre em

Engenharia Eletrotécnica e de Computadores

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FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

setembro, 2017

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À Mãe, ao Pai e à Nês

Having a place to go, is a home. Having someone to love, is a family. Having both, is a blessing.

Acknowledgements

Quero começar por agradecer ao meu orientador, o Professor João Murta Pina por toda a ajuda e paciência que teve durante a realização deste trabalho. À minha co-orientadora a Professora Maria Helena Ramos do Instituto Superior Técnico e ao seu doutourando Modesto Pérez, bem como a toda a equipa do Laboratório de Hidráulica um muito obrigada.

Quero também agradecer a todos os intervenientes que de uma forma ou de outra permitiram que este protótipo fosse construído: ao DEE; à Nova ID; À Henriques e Henriques; à KSB; à Caprari Portugal; à Janz Contadores de Água; à HidroGrés; à Candeias e Filhos; ao RICS Lab e a todos aqueles que aqui não estando aqui mencionados não são menos importantes.

Agradecer ao DEE todas as condições oferecidas durante a realização do curso e da dissertação. A todos os docentes que me acompanharam ao longo do meu percurso académico e a todos aqueles que de uma forma ou outra contribuiram para a minha formação enquanto enquanto aluna de uma prestigiada escola de engenharia e enquanto pessoa.

Quero agradecer ao meu colega António Rosa ('Toni') por ter sido o melhor companheiro nesta viagem académica recheada de altos e baixos, um amigo que conto levar para a vida.

À minha amiga Sardinha por tantas e tantas vezes ter sido o meu apoio, a irmã, a cozinheira, a lurdinhas, entre outros, uma vez *roomates*, para sempre *roomates*.

Aos meus amigos fora do curso: Bianca, Carol, Gabriel, João, Marie, Raquel V., Raquel C., Rita e Zé por sempre acreditarem em mim e estarem sempre presentes.

A todos aqueles que o curso me trouxe e que hoje são amigos.

Aos meus pais e à minha pequena irmã, obrigada por tudo. E mais qualquer coisa, as palavras serão sempre insuficientes, há coisas que não se explicam, sentem-se. Obrigada por serem os pilares da minha vida. Obrigada.

Aos meus avôzinhos e avózinhas, tios e tias, primos e primas por nunca duvidarem das minhas capacidades e por terem o maior orgulho em mim, seja lá o sítio onde estiverem. Um especial obrigada aos meus tios e prima da Margem Sul por toda a ajuda, uma parte desta caminhada foi deita com o vosso apoio.

Um obrigada especial ao Bé, por tudo.

"Many of life's failures are people who did not realize how close they were to success when they gave up."
Thomas A. Edison

Abstract

Over the last century, a giant leap in technological advancement has taken place. Technological progress is being made every day in a wide range of areas. But there are still problems to solve, such as large-scale energy storage and clean energy production.

The goals set by the European Community are clear: fossil fuels must be replaced by renewable energy sources in order to minimize the effects of global warming as well as to enable a sustainable development for future generations.

However, due to high volatility of renewable energy sources, such as solar, wind and water, there are still many challenges both at production side and upon control strategies, but these challenges have never been so big. Therefore, the production of energy in small installations is becoming an alternative, as a decentralized source of energy production.

In this study, a small-scale system aiming energy recovery through the reduction of pressure in water distribution networks is proposed. A pump operating as a turbine attached to an electrical generator is used to recover the energy that in normal operating conditions would be lost as heat.

The developed system also has educational and research purposes, allowing the development of new control techniques as well as of new power converters. In order to evaluate the operation of the proposed system, a prototype was created allowing the injection of the recovered energy in the distribution network.

The proposed methodology contemplates a theoretical design, the prototype construction, the definition of possible tests and validation and verification of the collected information. This system developed in this dissertation allows demonstrating the proposed concept, recovering energy without compromising the supply of final consumers.

Keywords: Pump as a turbine (PAT), pressure reduction, water distribution networks, renewable energy production

Resumo

Ao longo do último século, deu-se um passo gigante no avanço tecnológico. Existem desenvolvimentos diários numa vasta gama de tecnologias. No entanto, existem diversos problemas ainda por resolver, como o armazenamento de energia em larga escala ou a produção de energia cada vez mais limpa.

As metas impostas pela Comunidade Europeia são claras, referindo que a dependência de combustíveis fósseis tem de ser substituída por fontes de energia renováveis, de modo a minimizar os efeitos do aquecimento global, bem como a permitir um desenvolvimento sustentável para as gerações vindouras.

Neste estudo, propõe-se criar um sistema de pequena escala que permita recuperar energia através da redução de pressão em redes de distribuição de água. Uma bomba a funcionar como turbina, solidária com um gerador eléctrico, é utilizada para recuperar energia que, em condições normais de funcionamento, seria perdida sob a forma de calor. O sistema tem também um carácter educativo que permitirá o desenvolvimento de novas técnicas de controlo bem como de novos conversores de potência.

De modo a avaliar a operação do sistema, foi criada uma instalação que permitirá a injecção da energia produzida na rede. A metodologia utilizada para concretizar o objectivo inicialmente proposto contempla o dimensionamento teórico, a implementação da instalação, a definição de possíveis ensaios e a validação e verificação da informação recolhida.

O sistema desenvolvido na presente dissertação permite demonstrar o conceito proposto, a recuperação de energia sem comprometimento do abastecimento do consumidor final.

Palavras-chave: Bomba a funcionar como turbina, redução de pressão, sistemas de distribuição de água, produção de energia renovável

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Acronyms

EN	European Norm.
PAT	Pump as a Turbine.
PDP	Positive Displacement Pump.
PEAD	High Density Polyethylene.
PRV	Pressure Reduction Valves.
PVC	Polyvinyl Chloride.
WDN	Water Distribution Network.

Chapter 1

Introduction

The fast growing of the worldwide population is causing not only an increase in energy demand but also a concern among the specialists about environmental issues, leading to new studies and innovative solutions applied to the energy sector. One of the main boosters has been the identification of new technologies, capable of satisfying the needs of final consumers while being an alternative to energy production from fossil fuels.

The available resources to energy production, like the sun and the wind, are in many cases unpredictable solutions, needing in all cases backup solutions.

Renewable energy sources already fill consumers needs but due to their unpredictability, alternative renewable energy solutions must be developed. However, there are in many cases systems that can be optimized and which ultimately allow the use of energy which would be wasted in normal conditions.

A system to recover energy in a water distribution network is presented.

1.1 Context

Over the years, the planet demands for new strategies in order to prevent global warming and according to the Directive 2009/28/EC of the European Parliament EU, members must guarantee that 20 % of the consumption in UE is derived from to renewable energy sources, and also a decrease of 20% in CO2 emissions when compared to 1990.

The energy consumption in all the process that involves water (distribution, transport, recycling, irrigation) is an area of study that is quite underdeveloped by the fact that there are different variables that can influence the energy patterns of usage, according to a survey held by an ACEEE - American Council for energy. The same study also suggests that there are additional oportunities for energy efficiency as well as for water conservation [1].

According to recent studies, water supply systems worldwide can have energy losses of, on average, 40 per cent from the total water consumption. Such topic has concerned not only the environment experts but also managers of water supply systems. This concern is focused on the quest for economic and environmental self-sustainability of water distribution networks, which involves an high energy consumption and pressure control.

Moreover, several authors supported the use of pumps as turbines operating in water distribution networks, as a valuable solution not only for populations supply and irrigation, but also for energy production in a micro-scale, in a context of renewable energy production, with the advantage of a low cost installation and also because it is environmentally friendly. Economically, the choice of using a pump is only applicable if there is an excess of energy in the network, which in normal conditions would be lost, or if the output power generated by a turbine is too low (low flow).

According to [2] the use of pumps as turbines can be an alternative to common turbines not only because they are cheaper but also because they have a wide range of models available.

1.2 Objectives

Despite some studies in this field, the objective of this master thesis was to prove that a pump working as a turbine, inserted in a water distribution network, can produce energy and explore new techniques and control strategies, giving also the possibility to use a pump as a turbine in the network as a replacement of pressure reduction valves.

In order to demonstrate this concept a prototype was set up in a laboratory context at FCT NOVA whose main objective was to prove energy recovery but also to be used with an educational and research purpose.

This work includes a theoretical design, assembly and test of the experimental setup.

1.3 Dissertation Structure

This master thesis is divided in six chapters:

- Chapter One - Introduction to the developed work and the objectives to be achieved.
- Chapter Two - Literature review with the presentation of hydraulic concepts, relevant legislation and network electric connections.
- Chapter Three - Presentation of the system design.
- Chapter Four- Material selection and implementation, explanation of the methodology used for both material selection and system implementation .
- Chapter Five - Experimental results presentation, discussion of the obtained results.

- Chapter Six - Main conclusions about the developed work and possible future work.

1.4 Acknowledgements

This research was partially supported by KSB, Caprari, Henriques and Henriques, Janz - Water Meters and Schneider Electric. The author thanks the provided resources and all the helpful information and assistance for the accomplishment of this study.

Chapter 2

Literature Review

Water is the driving force of all nature.
Leonardo da Vinci

This chapter provides an overall view of energy production by performing a pressure reduction in Water Distribution Networks as well as discuss the actual technologies and proposed solutions for this problem. It gives a brief explanation of the fundamental principles behind it.

A contextualisation about Portuguese regulation is also made so that experimental setup and test conditions are brought together as close to reality as possible.

2.1 Basic Hydraulic Concepts

In this section a description of principles and concepts that support the initial idea of this work.

- **Flow**

Flow is defined as the amount of a certain fluid that passes through a surface (pump or turbine) within a period of time. Two parameters of flow can be considered: volume flow (Q) and mass flow (Q_m). Volume flow, which can be read from a pump/turbine curve, is the quantity of volume that a pump/turbine can move per unit of time. This parameter is measured in m^3/h and is independent from the liquid density (ρ). On the other hand, mass flow (Q_m) is the mass of fluid moving per unit of time. This parameter is measured in kg/h. This is an important parameter in the design of heating, cooling and air conditioning systems because fluid density changes with temperature and that influences the quantity of mass flow that a pump or a turbine can move. Both parameters are related using the equation 2.1.

$$Q_m = \rho Q \tag{2.1}$$

- **Pressure**

Pressure is defined as force per unit of area. The total pressure p_{total} of a fluid is the sum of its static p_{static} and dynamic pressure $p_{dynamic}$.

Static pressure can be measured with a pressure gauge placed perpendicular to the fluid flow or in an non moving fluid, see figure 2.1.

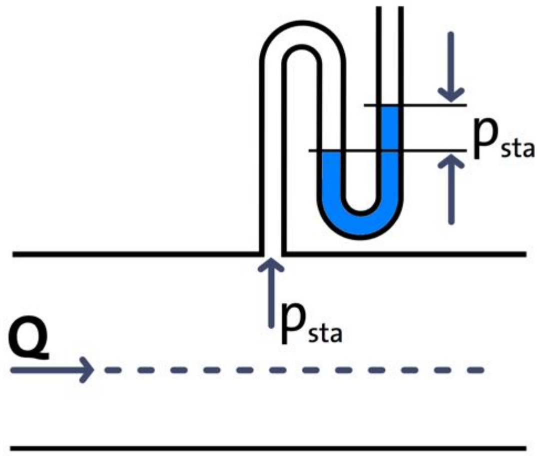


Figure 2.1: Illustration of static pressure measurement

Dynamic pressure is dependent on fluid velocity (v) and density (ρ), and cannot be measured using a pressure gauge. Instead, it is calculated using the equation 2.2.

$$p_{dynamic} = \frac{1}{2}\rho v^2 \tag{2.2}$$

Dynamic pressure is specially important because it can be converted into static pressure when the velocity of fluid changes. When the pipe diameter increases from D_1 to D_2, the liquid velocity will decrease from v_1 to v_2 (figure 2.2). If the effect of friction loss is neglected, the sum of static and dynamic pressures is constant through the horizontal pipe, see equation 2.3.

$$p_1 + \frac{1}{2}\rho {v_1}^2 = p_2 + \frac{1}{2}\rho {v_2}^2 \tag{2.3}$$

As shown in figure 2.2, when the diameter is increased, the static head, measured in pressure gauge p_2, will also increase.

In most pressurised systems the effect of dynamic pressure is negligible when calculating the head of a pump/turbine.

Pressure can be measured in different units depending on application, see Appendix (II). IS Unit of pressure is Pascal [Pa]. Relating to pressure measurement, the main factor

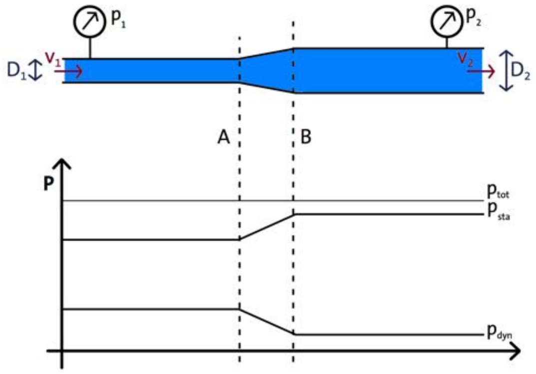


Figure 2.2: Effect of pressure increase with velocity decrease

is to know the exact point of reference for pressure measurement. So, it is essential to know the absolute and the gauge pressure:

- **Absolute pressure** is the reference value (absolute zero for pressure 0 atm). This parameter is specially important in cavitation calculation.
- **Gauge Pressure** is the pressure above normal atmospheric pressure (1 atm). Usually the measurement devices calculate the difference between the system pressure (gauge pressure) and the atmospheric pressure.

Head is an expression that allows determining how high the pump can lift a liquid. It is measured in meters and is independent from the liquid density. Equation 2.4 shows the relation between pressure and head. Usually the values defined by manufactures are expressed in *bar* which is equal to $10^5 Pa$.

$$H = \frac{p}{\rho g} \tag{2.4}$$

Where,
H is the head $[m]$
p is the pressure $[Pa = N/m^2]$
ρ is the liquid density $[kg/m^3]$
g is the acceleration of gravity $[m/s^2]$

Energy conversion

Hydropower generation has as a principle the conversion of hydraulic potential energy of a flow into electric energy, which corresponds to a differential net head, usually denominated as $"H"$.

The energy of the flow is associated to the gravity energy through natural or artificial water falls, commonly in rivers or through hydraulic systems, composed of pressurised pipes or penstocks, or by mixed hydraulic conveyance system composed of canal and penstocks.

The principle of energy conservation, the energy balance of a steady flow from an arbitrary point A to an arbitrary point B will obey Bernoulli equation (2.5):

$$Z_A + \frac{p_A}{\rho g} + \frac{\alpha_A {V_A}^2}{2g} = Z_B + \frac{p_B}{\rho g} + \frac{\alpha_B {V_B}^2}{2g} + \Delta H_{AB} \tag{2.5}$$

where Z is the *elevation head* (m) at the point of interest (above a reference plane); p_A and p_B (Pa) is the pressure at the center of gravity of the flow cross sections; V (m/s) is the average flow velocity; ρ (kg/m^3) is the water density, g (m/s^2) is the gravity acceleration and α represents the numerical coefficient accounting for the non-uniform velocity distribution; equation 2.5 expresses the difference between total heads at A (H_A) and B (H_B) is equal to the headloss ΔH_{AB} between the two flow cross sections, where the head is the total flow energy by weight of the flowing water, [3].

2.1.1 Principles of Fluid Dynamics

In this section the fluid properties will be described. A fluid can be either a liquid or a gas, and its defined by the deformation under an applied shear stress (equation 2.6).

$$\tau = \frac{F}{A} \tag{2.6}$$

where, τ is the shear stress expressed in Pa; F the applied force, expressed in N or kg·m/s; A the cross sectional area of a material parallel to applied force, expressed in m^2.

- **Water properties: Density, Fluid Mass and Weight**

Density ρ is used to define and characterize the mass of a fluid system. In SI Units the density is expressed in kg/m^3. Variations in pressure and temperature will have a small effect in ρ, most of the times the value is nearly constant; the density of water is about 1000 kg/m^3 at 20°C.

Anther important relation is specific volume, $\nu = \frac{1}{\rho}$ and is the volume per unit mass (inversely proportional to density).

Specific weight γ is the weight of a fluid per unit volume, and this value is related to the density $\gamma = \rho g$. This value, expressed in N/m^3, is used to characterize the weight of the system. Under conditions of standard gravity (g= 9.807 m/s^2), water at 20°C has a specific weight of 9790 N/m^3.

- **Viscosity**

Viscosity (μ) is the quantitative measure of a fluid's resistance to flow. The previous properties of fluid (ρ e γ) are not enough to characterize how fluids behave. Two fluids (water and oil) can have approximately the same value of density.

Viscosity is defined as:

$$\tau = \mu \frac{\partial u}{\partial y} \tag{2.7}$$

where viscosity μ is expressed in kg/m·s; differential equation $\frac{\partial u}{\partial y}$ defines the slop of each line, depending on material; $\frac{u}{y}$ is the rate of shear deformation.

Equation 2.7 can be used where velocity does not vary linearly with y, such as, fluids moving through a pipe.

- **Compressibility**

Compressibility is a fluid property, directly related with the volume change of a fluid.

A fluid is defined as a substance that deforms continuously when acted under the influence of a force. The force is created whenever a tangential force acts on a surface. Generally, fluids can be compressible (e.g. almost every gas) or incompressible (e.g. water). In the case of compressible fluids their volume is dependent on pressure and temperature. Liquids can be considered as incompressible for almost every engineering application (except in hydraulic shock calculation) as their volume is independent from pressure. For example, at atmospheric pressure and 20°C it would require a pressure of 215 bar to compress a unit volume of water only 1%. The pressure to cause an exchange in volume is too large.

- **Vapor Pressure**

Vapor pressure is the pressure at which a liquid boils. Water vapor pressure at 20°C is 2330 N/m^2 and at 100°C is equal to the normal atmospheric pressure.

When the pressure of a liquid drops to the respective vapor pressure the liquid starts to boil. If the drop in liquid pressure is due to fluid flow, vapor bubbles can be formed. This process is called cavitation.

2.1.2 Fundamental Principles of Hydrokinetics and Hydrodynamics

In this section fluids main characterization based on flow type will be explained.

- Basic Concepts

Water flow/Discharge is defined as the volume that crosses a section per unit of time. $Q = \int_s V ds = V \cdot A$

- Fluid Flow Regime

Fluid flow can be categorized according to different criteria such as its variation through time, space and flow pattern.

Analysing a fluid flow through time, it is possible to classify it as steady or unsteady. If there are variations in velocity, pressure, density and discharge, for a certain period of time, the fluid is classified as unsteady. Steady flow is rare in a practical scenario.

Based on flow patterns, fluid flow can be classified as rotational or irrotational.

When the flow of a fluid is moving with a moderate speed, the fluid has fluid layers moving past each other. Such type of flow is designated as laminar flow. For a laminar flow in a pipe, only one component of velocity is defined (equation 2.8). This is a type of flow characterized by smoothness and regular trajectories of fluid particles.

$$V = u\overrightarrow{e_x} \tag{2.8}$$

where V represents the the punctual velocity, expressed in m/s and $\overrightarrow{e_x}$ x represents x component of the velocity curve as a function of time at a point A in the flow.

On the other hand, when the flow speed of one calm layer increases, these smoothly moving layers start moving randomly and will increase the flow velocity, the fluid particles become completely random and no such laminar layers exists any more. In this kind of turbulent flow, the main component of velocity along the pipe is unsteady (random) and accomplished by random components normal to the pipe axis, see equation 2.9.

$$V = u\hat{e_x} + v\hat{e_y} + w\hat{e_z} \tag{2.9}$$

where V is the punctual velocity, expressed in m/s; $\overrightarrow{e_x}$, $\overrightarrow{e_x}$ and $\overrightarrow{e_z}$ are the normal components along the pipe axis.

It is possible to observe those types of fluid flow regime in domestic places, after the opening of a tap, before the water reaches the sink; laminar flow is presented, after the water reaches the sink, the flow is characterized as turbulent, figure 2.3 illustrates the effect of both fluids passing through a fluid body.

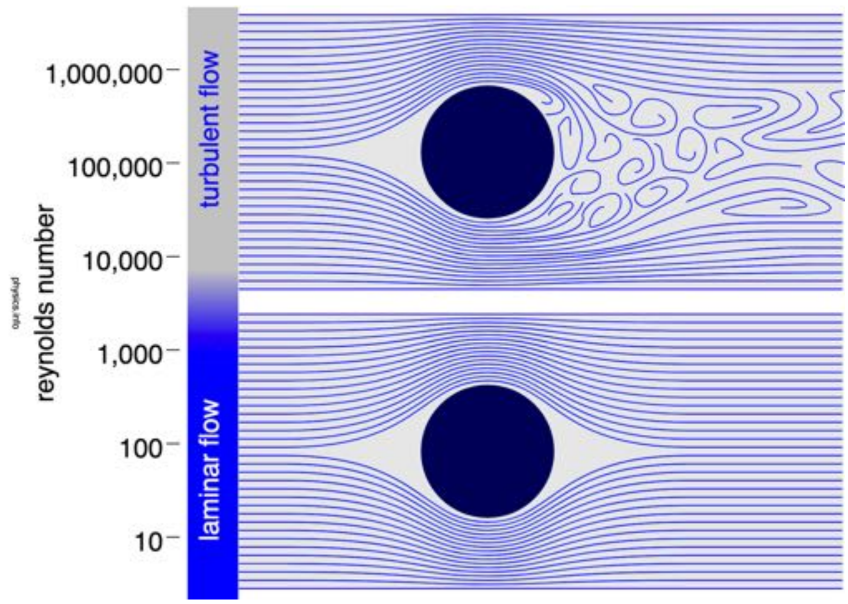


Figure 2.3: Fluid Flow Regime: Laminar and Turbulent

Shear stress in turbulent flow is larger than those in laminar flow [4].

- Reynolds Number

The Reynolds number, defined in equation 2.10, is the ratio of inertia to viscous effects in the flow. This number is used as a criteria to distinguish between laminar and turbulent flow and will increase with the flow velocity of the initial forces. The flow in a round pipe is laminar if the Reynolds number is less than approximately 2100 and when the value is greater than 4000 the flow is turbulent. Flow can change between laminar and turbulent conditions in a randomly way. This state is considered the transitional flow.

$$Re = \frac{\rho V D}{\mu} \tag{2.10}$$

where Re is the Reynolds Number, expressed in (kg·m/s^2)/N but, since 1 N = kg·m/s^2 this is a dimensionless parameter; ρ is the fluid density, expressed in kg/m^3; V the mean fluid velocity, expressed in m/s; D the pipe diameter, expressed in m; μ the fluid viscosity, expressed in N·s/m^2.

Reynolds number is specially important in losses calculation; a detailed explanation is found in chapter 3.1.2.

2.2 Water Distribution Networks

In this section what is a water distribution network and its main elements as well as how Portuguese Regulation defines such type of network is explained.

2.2.1 General Overview

Water distribution systems provide water for human consumption, piped water is also used for washing, sanitation, irrigation and fire-fighting. However, before the water reaches the final consumer many processes are behind it: capture, treatment, elevation, transport, storage and distribution, [5].

The water supply system can be divided in three main stages [6]:

- Raw water extraction and transport;
- Water treatment and storage;
- Clean water transport and distribution.

In both transportation and distribution, water is conveyed through a network of pipes, stored in the middle points and pumped if necessary, to guarantee the desired pressure and demand, that can vary through different parts of it. This is a factor that has a huge impact in the network configuration.

2.2.2 Piping

Pipes are one of the most important components in water networks (distribution and transport) because they allow to carry the water from a certain point A to B and reach the final consumer.

Pipes can be made of different materials, may have different diameters, service connections or valves. Pipe specifications will depend on the final purpose.

Depending on the site location of the water sources, the pipe diameters will change. Figure 2.4 represents a water distribution network with different pipe diameters that supplies around 350.000 consumers.

The water, in this case, is pumped from the reservoir via a main trunk (D = 600 mm) for the secondary network with pipe diameters D=300-500 mm and then distributed by the pipes D = 100 and D = 200 mm. Pipes diameter will decrease as the consumption point approaches.

Figure 2.4: Distribution system in Hodaidah, adapted from [7]

Pipes material must be carefully chosen during the design phase, material choices as steel pipes can lead to rust formation as a result of aging process. So, there are a lot of possibilities: CI (cast iron), steel, PVC (Polyvinyl chloride) and GRP (Glass Reinforced Pipes). According to [8] when comparing CI pipes to PVC Pipes, CI pipes required higher standards in water treatment when compared to other pipe materials.

A detailed example of two different pipe materials are presented. A steel pipe (figure 2.5) and a PEAD (high density polyethylene) pipe (figure 2.6).

2.2.3 Connection Points

There are several types of joints that can be used to connect the different pipes in a network: rigid, semi-rigid and flexible.

The type of joints will depend both on pipe material and site application.

Figure 2.5: Steel pipe

Figure 2.6: PEAD pipe

Sometimes the solution to connect two pipes implies welding. This is the cheapest join junction for steel pipes of larger diameters (2.7), although these joints do not allow any pipe route deflection and change in direction.

Figure 2.7: Welding of steel pipes, adapted from [7]

Another example of connection points are fittings, see figure 2.8, mostly used when there is a change in pipe diameter and/or material, pipeline direction or when it is necessary to install valves or measurement devices.

It is important to mention that there is a large variety of joint solutions available, and the best solution depends on the desired application. Connection points or joints are the part of the network were more leaks occur, resulting in losses of water as well as significant pressure deviations.

Figure 2.8: DI Fittings (Manufacturer: Saint-Gobain)

2.2.4 Valves

Another important element in Water Distribution Network (WDN) are the valves. There is a widely range of models available in the market, and each application can have a different type of valve.

Valves have three main tasks, [6]:

- Flow and/or pressure regulation (flow control valves, pressure reducing or pressure sustaining valves, etc.);
- Exclusion of parts of the network in order to execute maintenance or emergency operations (section valves);
- Protection of the reservoirs and pumps (e.g. float valves, non-return valves).

For the purpose of this study the most important valves are the ball valve (figure 2.10) and the pressure reduction valve (figure 2.9).

Figure 2.9: Pressure Reduction Valve from Hawle company

2.2.5 Portuguese Regulation

In this section the Portuguese Legislation and the applied standards for water distribution networks, will be described.

Figure 2.10: Ball Valve from Pinto e Cruz company

- **Legislation**

In Portugal the legislation for water distribution networks follows the Regulatory Decree no. 23/95 of 23th of August, DR 23/95, with the definition of the rules for public and building systems of drinking water distribution and drainage of waste water. This Decree is based on an adaptation of an European standard European Norm (EN) 806 which specifies installations inside buildings conveying water for human consumption.

However, under the article no. 2 of DR 23/95 each city must adapt the current legislation and create specific norms. Water supply and distribution is regulated by three type of entities: city councils, municipal companies and private companies. Those are called service providers, and different management models are possible.

- **Hydraulic Design (according to DR 23/95)**

The design of a water distribution network must be done according to the minimum consume demand. The design must consider the number of inhabitants as well as their needs. For example, assuming a population with more than 50,000 inhabitants the minimum consume is 175 L/inhabitant/day. There are also some consume references for special buildings such as schools, hotels, restaurants, hospitals and emergency networks.

According to DR 23/95, in building branches minimum and maximum pressures of respectively 100 kPa (1 bar) and 600 kPa (6 bar) are established. Concerning flow the numbers are between 80-175 L/inhabitant/day for an inhabitants range from 1,000 to 50,000.

The maximum, statics and service, pressure measured at the sea level must be under 600 kPa (6 bar). During the day, the maximum variation is 300 kPa (3 bar), in each node of the system.

For the hydraulic design, flow velocity, during peak hours, must be bellow 0.5-20 m/s. This value is given by equation 2.11.

$$V = 0.127D^{0.4} \tag{2.11}$$

where V is the limit fluid velocity, expressed in m/s; D is the intern diameter of the pipes, expressed in m.

It is also established that the minimum nominal diameter for distribution is 60 mm (for locations with less than 20,000 inhabitants).

- **Type of material**

Regarding the type of material of the pipes, the regulation defines that it can be:

- Asbestos cement;
- Cast iron;
- Copper;
- Stainless steel;
- Galvanized iron or steel;
- Polyvinyl Chloride (PVC);
- High Density Polyethylene (PEAD);
- Other types of material that gather the proper conditions.

- **Branch connection**

Connection branches with building systems must be done with good conditions of pressure and flow in order to guarantee a good quality of the service.

The minimum flow is specified in the design of building systems, and the fluid flow velocity must be between 0.5 m/s and 2 m/s, according to the available pressure in the network.

After the distribution network the minimum diameter of branch pipes is 20 mm.

Fittings and accessories for connecting elements must assure no leaks and an easy manoeuvre in case of a major trunk in the network (fault case).

Each and every network needs to be equipped to respond if any fault occurs. The network must have isolation valves placed in strategic points, allowing an easy operation with no interruption of the supply. This type of valves must be placed in:

1. Branch connections;
2. Before and after network elements, to provide a quick response, in case there is a need to replace or restore one;
3. Along the distribution line (no more than 1,000 m spacing);
4. Major junctions (2 or 3 valves).

The installation of pressure reduction stations is mandatory in order to decrease the pressure downstream. These stations are equipped with Pressure Reduction Valves (PRV) installed in accessible places. Downstream must be equipped with a sand filter and upstream with a manometer or with a device that allows an easy pressure management. PRV upstream and downstream must have isolation valves, as well as a bypass system in order to guarantee system efficiency.

Water distribution networks must have active devices to measure the amount of water flowing. Flow meters must be installed in protected and accessible places to allow a correct measurement. Furthermore, flow meters must be placed in building systems of all end consumers, output reservoirs, pumping stations and strategic places to allow system efficiency measurement. There are different types of parameters to consider when selecting a flow meter, for example, the range of flows to be measured, required precision, maximum head loss, service pressure, diameter and pipeline position.

2.3 Turbomachinery

The prefix turbo derives from the latin *'turbo'* meaning "spin"or "whirl".

Turbomachines are devices that transfer energy either to, or from, a moving flowing fluid by the dynamic action of one or more moving blade rows, converting hydraulical energy into mechanical energy and vice-versa.

Turbomachines are divided in two big groups: those that supply energy to the fluid, called *pumps*, and those that extract energy from the fluid, called *turbines* [3].

A rotor or an impeller can do positive or negative work, depending on the required effect in the machine. These momentum changes are linked with pressure changes that occur due to fluid movement, see figure 2.11, [9]. Rotor and impeller are connected to a rotating shaft, hence the name tubomachinery.

Based on the flowing fluid, turbomachines can be classified as:

1. Hydraulic machines (incompressible fluids): pumps, hydraulic turbines, fans, marine propellers;

2. Thermal machines (compressible fluids): gas turbines, vapor turbines, compressors, airplane propellers, wind turbines.

In hydraulic machines, turbines and pumps have different characteristics and applications, and they can be classified in different ways, according to figure 2.12.

As the fluid particle moves, both gravity and pressure forces do work on the particle. Recall that the work done by a force is equal to the product of the distance the particle travels times the component of force in the travel direction.

Work/energy principles: the work done on a particle by all forces acting on the particle is equal to the change of the kinetic energy of the particle.

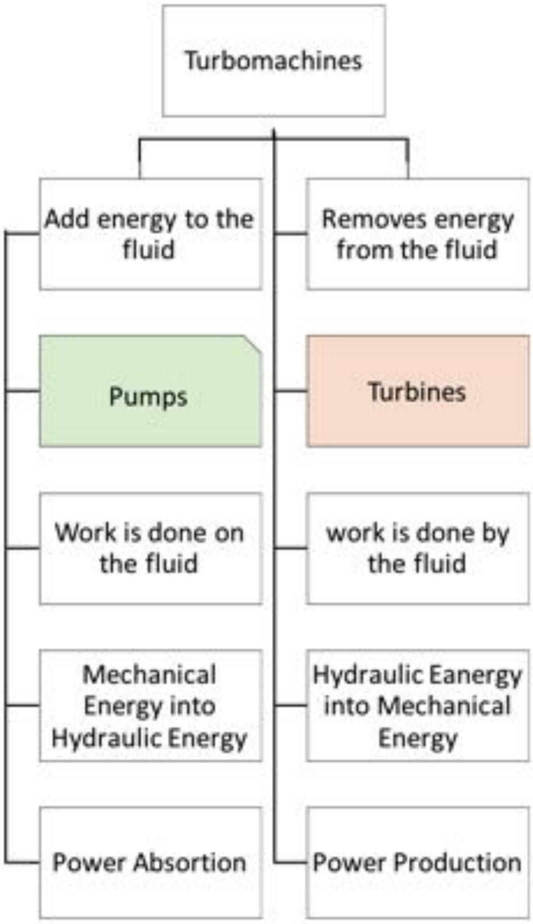


Figure 2.11: Pumps and Turbines

2.3.1 Turbines

Hydraulic turbines are specially designed to convert a certain hydraulic energy (potential and kinetic energy available in water falls) into mechanical energy of rotation that generates electrical energy, see figure 2.13.

Turbines can be differentiated according to:

1. Operating head:
   High head: above 300 m e.g. Pelton wheel;
   Medium head: 30-300 m e.g. Francis Turbine;
   Low head: 3-30 m e.g Kaplan Turbine.

2. Direction of the internal flow, [10]:
   Tangential Flow: Flow tangent to the rotor;
   Axial Flow: Flow without significant radial component in the rotor (e.g. Kaplan Turbine);
   Radial Flow: Flow with significant radial component at the rotor outlet or inlet (e.g. Francis Turbine);

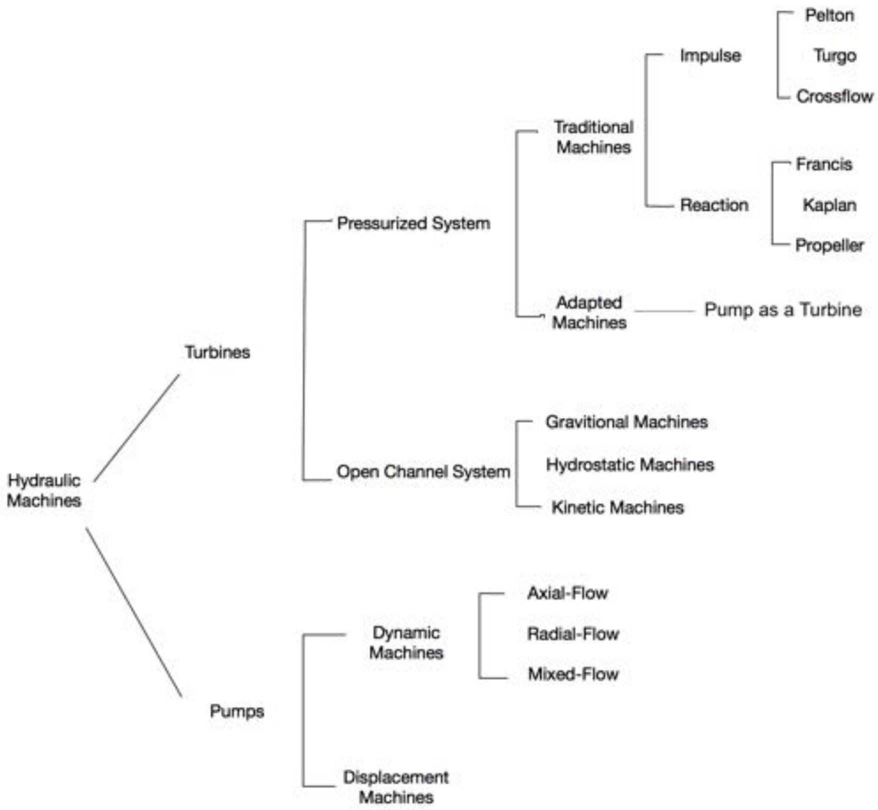


Figure 2.12: Hydraulic Machines

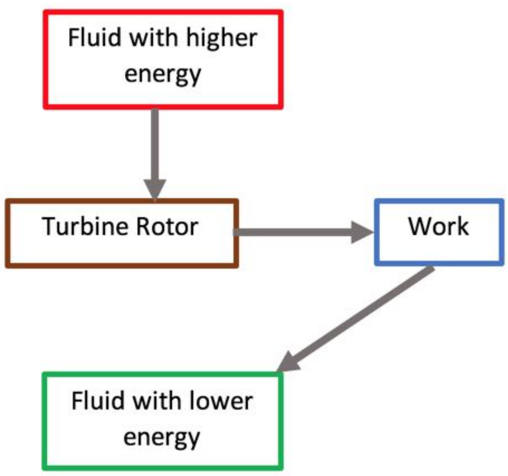


Figure 2.13: Turbine scheme

Mixed Flow (e.g. Pelton wheel)

3. How potential energy is converted into mechanical energy [11]
   Impulse turbine (e.g. Pelton)
   Reaction turbine (e.g. Francis)

Considering the purpose of this work, only the last classification will be considered.

2.3.1.1 Impulse Turbines

An impulse turbine is characterized by the pumping of the water at a high pressure to a nozzle where it expands to atmospheric pressure. The emerging jet impacts on the blades (or buckets) of the turbine, which produces the required torque and power output, [9], see figure 2.14. In this kind of turbines the flow energy is converted into kinetic energy before transformation in the rotor, making it more suitable for applications that require an high head and low power.

An impulse turbine needs a chase only to control the splashing and to protect against accidents. Usually this kind of turbines are cheaper than reaction turbines because no special pressure chase is needed.

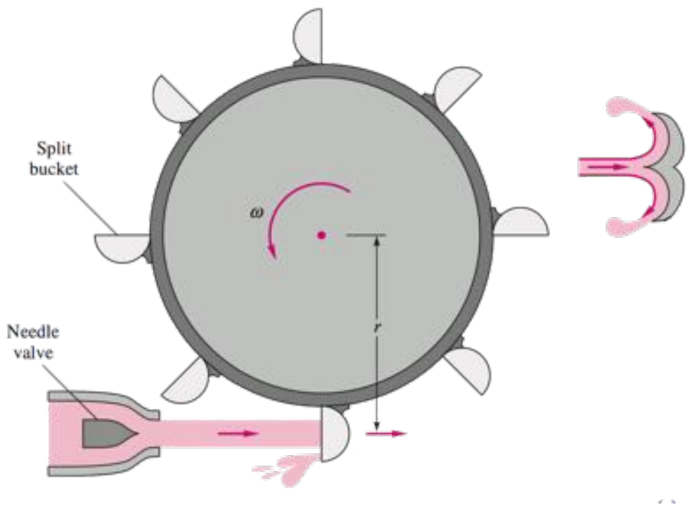


Figure 2.14: Impulse Turbine

Pelton, turgo and cross-flow turbines will be presented in sequel.

- Pelton Turbine

Pelton turbine (free-jet) is the most widely used model of this type. Many variations of impulse turbines existed prior to this one but they were less efficient than Pelton's design, [11]. It is composed of a runner/wheel(figure 2.15 (1)) that is secured on the shaft (figure

2.15 (2)) and one or more nozzles (maximum 6) (figure 2.15 (3)) to which the water is supplied from the pipeline (figure 2.15 (4)).

The runner/wheel consists of a disk with a series of blades (usually called buckets (figure 2.15 (5))) with the shape of a double spoon, around the periphery. Each bucket has two curvilinear surfaces separated by a spear. The runner and the nozzle are assembled above sea level, for that reason the runner rotates in the air (does not work submerged), figure 2.15. One or more nozzles are mounted in a way that each nozzle directs its jet along the tangent to the circle through the centers of the buckets.

As the jet (figure 2.15 (6)) hits a bucket, the spear splits the oncoming jet into two equal streams so that each flow goes from on side to the other of the curvilinear surface in a direction nearly opposite that of the incoming jet.

The jet of water coming from the nozzle hits the buckets of the runner which allows the transformation of the kinetic energy of the water into rotational mechanical energy. The nozzle has a movable needle inside which allows the control of the discharge, as shown in figure 2.16b.

The nozzle has also a deflector (figure 2.16) that operates as a device control in case a load rejection occurs, making an alteration of the jet direction enabling its slow closure, which allows to control overpressure in the penstock and overspeed of the runner [12].

The quality of a Pelton Turbine is regulated by the change rate of the water flow throught it, this is ensured by the needle. When the needle covers the totality of the nozzle the flow rate is equal to zero [13].

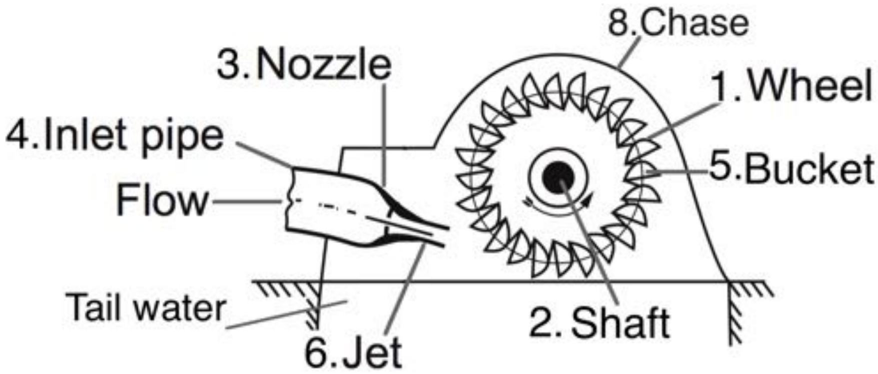
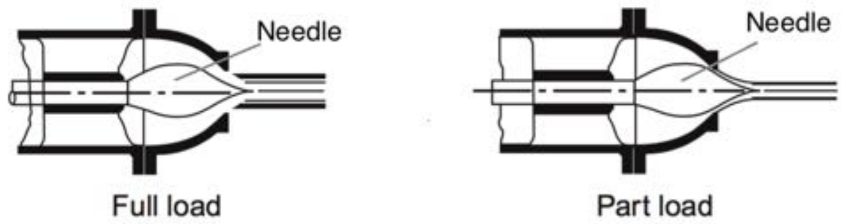


Figure 2.15: Pelton Turbine

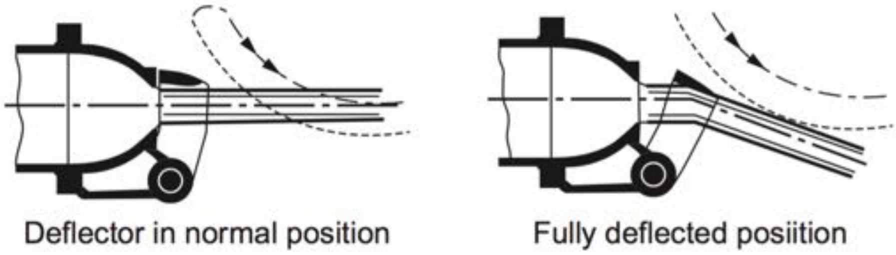
- **Turgo Turbine**

Turgo turbine was developed by Gilkes Energy Company in 1919 and is a variation of Pelton turbine free jet impulse. It is designed for medium head applications. It is less efficient than a Pelton but it has the capacity to generate the same power, and has a runner that can deal with high discharge variations [14].

The differences between Pelton and Turgo turbines are the design of the buckets and blades (figure 2.17a). They are shaped differently, in a Pelton turbine the jet strikes the



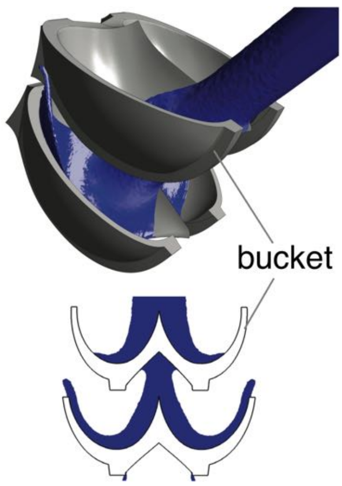
a Needle



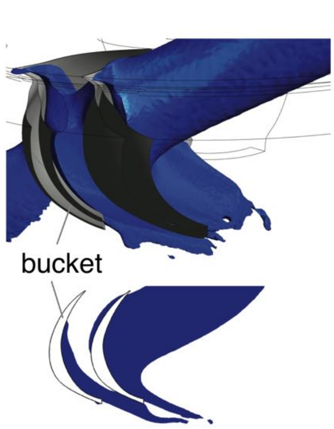
b Deflector

Figure 2.16: Regulating of speed

centre of the bucket at a right angle and then split into two (figure 2.17a). Unlike the Pelton, in Turgo turbines, the jet is designed to enter the runner in a different angle (typically $20 \cdot C$ figure 2.18), pass through the wheel, and discharge from the other side (figure 2.17). Also, the discharged fluid and the incoming jet do not limit the flow rate. Due to these differences, it is possible to have a smaller diameter runner than a Pelton and achive the same power [15].



a Bucket of a pelton Turbine



b Bucket of a turgo Turbine

Figure 2.17: Bucket: pelton vs turgo, adapted from [15]

There are several advantages to the use of a Turgo turbine: the runner is cheaper than a Pelton wheel and the specific speed is higher, making it possible to have a greater

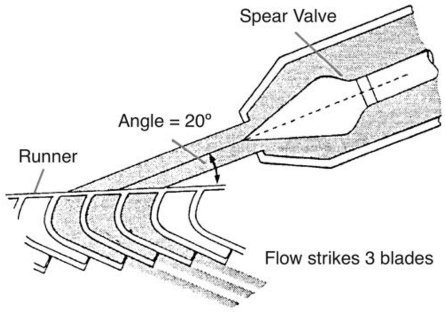


Figure 2.18: Turgo Turbine: Angle of strike, adapted from [16]

flow with the same diameter as a Pelton, reducing the generator costs which decrease the installation costs. Both turbines can have a horizontal or vertical orientation.

- **Cross-Flow Turbine**

The cross-flow turbine, also designated by Ossberger, Banki or Mitchell, is used for a wide range of flow and heads between 5 and 200 meters. This turbine has its runner shaft parallel to the ground in all cases, it comprises a drum-shaped runner with two parallel disks connected together near their border by a series of curved blades. In operation, a rectangular jet directs the flow to the full length of the runner. The water strikes the blades and transmits most of its kinetic energy. It then passes through the runner and strikes the blades on the exit, transferring a small amount of energy before leaving the turbine.

Compared to other turbines, cross-flow has a low efficiency that can be improved by the inducement of a partial vacuum inside the chasing; such vacuum improvement is expensive since it requires an air seal around the runner shaft as it passes through the chasing. This can be achieved by the placement of a draft tube bellow the runner which remains full of tail water at all times. Any decrease in the water level induces an higher vacuum which is limited by the use of an air bleed valve in the chasing, figure 2.19.

The water passes through a guide-vane located upstream of the runner and has a double action on the blades of the runner.

This simple design makes this turbine cheap and easy to repair in case of runner brakes due to the important mechanical stresses, [9].

It is an alternative when there is enough water, defined power needs and low investment possibilities, such as for rural electrification programs.

2.3.1.2 Reaction Turbines

In this kind of turbines only a part of the pressure drop occurs before the turbine entry. The remaining pressure drop takes place in the turbine itself; the flow fills all the passages in the runner, unlike the Pelton turbine where for each jet, only one or two buckets were directly in contact with water at the time; the guides vanes are used to control and direct

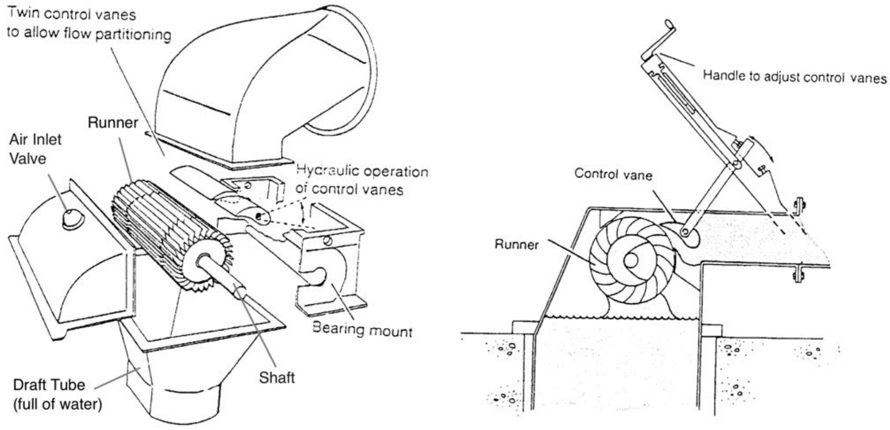


Figure 2.19: Crossflow Turbine, adapted from [16]

the flow; a draft tube is at the exit of the turbine in order to transform velocity head to static head due to its increasing area. The pressure of the water gradually decreases as it flows through the runner. This type of turbines are so called reaction turbines because of this pressure change [9].

A reaction turbine, apart from the runner, is composed of runner vanes that are curved and surrounded by a guide wheel. They also have a closed chamber (spiral case), where the flow takes place in transforming part of pressure energy into rotational mechanical energy of the runner. A movable guide vane (or wicket gate) guides the flow around the runner, making the regulation of the turbine discharge to the draft tube. The draft tube allows to minimize losses [11].

- **Francis Turbine**

Francis turbines usually have a vertical axis (small machines can have an horizontal axis). This turbine is of radial or mixed flow with adjustable wicket gate. It is used for low/medium heads and high flow rates.

The water enters through a spiral casing called a volute or scroll that surrounds the runner. The area of cross-section of the volute decreases along the flow path in such a way that the the flow velocity remains constant. After the volute the water enters in a ring of stationary guide vanes that direct the flow in a certain angle according to the demand of power, [9].

While flowing through the runner (figure 2.20), the angular momentum of the water will decrease while work is supplied to the turbine shaft. The flow leaves the runner axially into the draft tube and finally the flow enters the tailrace.

The exit of the draft tube must be submerged bellow the level of the water in the tailrace to guarantee that turbine remains full of water. The draft tube also has the function of diffuser.

- **Propeller and Kaplan Turbine**

Figure 2.20: Francis turbine: runner

Propeller and Kaplan turbines are axial flow reaction type and are specially designed for low heads, these turbines generate power from much lower heads than Francis Turbines. Kaplan turbines can be defined as a more sophisticated version of the propeller turbine [16].

The basic version of propeller turbine consists of a propeller, similar to ship's propeller, fitted inside a continuation of the penstock tube. Three to six blades are used; in case of very low head units, only three are necessary. This turbine is an option when both flow and head remain constant.

In this kind of turbines the water flow is done by the use of wicket gates just upstream the propeller, figure 2.21.

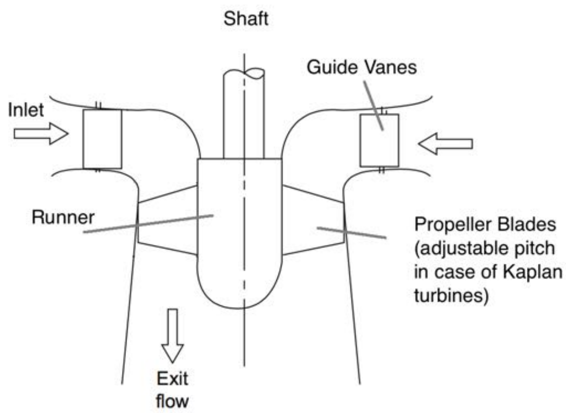


Figure 2.21: Section of an Axial flow (propeller) turbine, adapted from [9]

On the other hand, Kaplan turbines have adjustable runner blades that can have adjustable guide vanes or not, being classified as double regulated or single regulated, respectively. This feature allows for a better adaptation to different flow values and an higher efficiency.

Kaplan turbines differ from propeller turbines by having pitch runner blades, where wicket gates are carefully designed to induce tangential velocity or 'whirl' in the water. Both types of turbines can be arranged in an open flume (micro generation) or with a spiral case of concrete or cast iron, similarly to Francis turbines.

2.3.1.3 Pumps

Generally, a pump is a machine that adds energy to anything flowing through it. The spontaneous tendency of anything is to flow from high potential to low potential and this natural tendency is harnessed in many applications. But the pump does exactly the reverse; it forces something to move from low potential to high potential. For this purpose, pumps have to use energy and by their functioning they transfer that energy to the substance flowing through them.

Fluid pumps or hydraulic pumps move fluids and displace them from one position to another and in this course, energize them. In fluids, this energy shows changes in its pressure and velocity. Similarly, heat pumps move heat from low temperature to high temperature against its natural tendency.

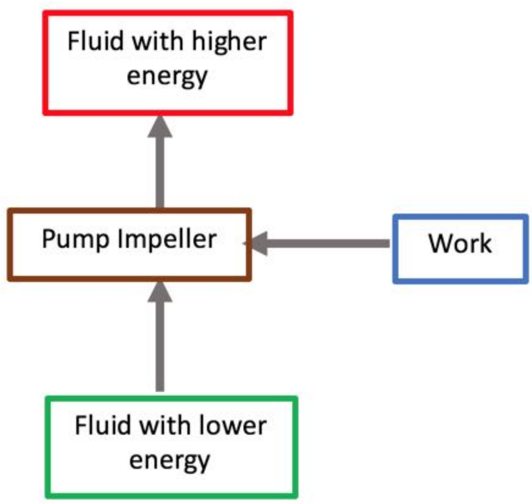


Figure 2.22: Pump

2.3.2 Pumps Classification

Pumps classification depends on the application, materials of construction, the liquids they handle or their orientation in space. Generally the classifications are limited in scope and overlap each other. A basic system of classification proposed by [17], defines the principle by which energy is added to the fluid, figure 2.23.

There are two basic types of pumps: positive displacement (static type) and dynamic type.

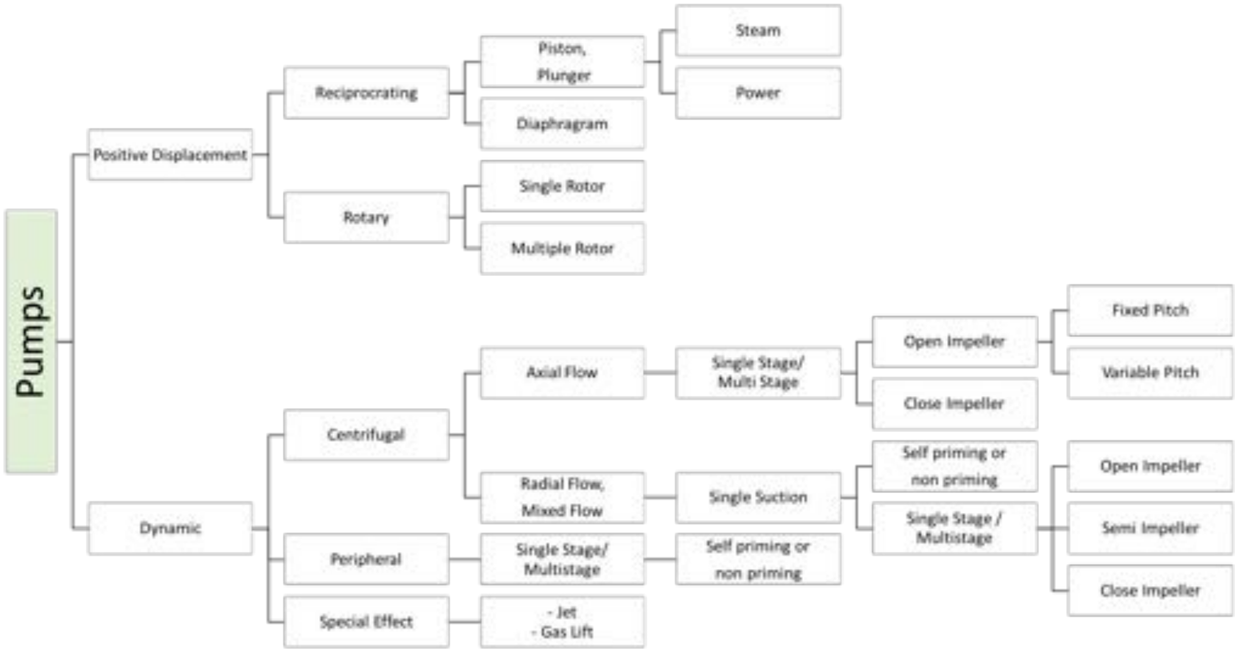


Figure 2.23: Pumps Classification, adapted from [17]

Positive displacement pumps convert energy due to the variation of volume (energy is periodically added to the fluid). A cavity is open and the fluid enters the inlet, then the cavity closes and the fluid is squeezed through an outlet, which forces the fluid to make the same movement (e.g. human heart and a tire pump).

In dynamic pumps, the flow is created because of the fluid movement in the impeller blades, that allows the rotation of the runner (energy is continuously added to the fluid). There is also no closed volume, the fluid increases the momentum while moving across open sections and then its high velocity is converted to a pressure increase due to the exit through the diffuser section [3, 17].

Usually, dynamic pumps provide an higher flow rate with moderate pressure rises, and contrary to Positive Displacement Pump (PDP) they can operate at very high pressure but producing low flow rates.

Dynamic pumps of centrifugal type are the most commercially used devices, because they are cheaper and have a simple design [2].

2.4 Pump as a Turbine

The starting date of pumps used as turbines (PAT) remains unclear but in 1931 Thoma and Kittredge were trying to obtain the complete characteristic pump curve and they made a remarkable discover: pumps could operate very efficiently as turbines. In later years, the chemistry industry became an area for the application of PAT's as a way to recover energy.

Although the technology for using the PAT to produce energy was not available in the earlier years, advances in electrical machinery control techniques, rotation sense and torque allowed the chance to produce energy when a pump rotates in the reverse mode [18].

The type of pump in a PAT is usually a centrifugal pump, this is the most suitable option for micro-hydro; when this kind of pump is used no adjustment is possible [2].

In recent years, several researchers have focused their work on an efficient management of WDN (water distribution network) [19]. Mini hydro power plants are a common practise in WDN [20, 21, 22] where a pressure drop and a stable discharge were applied to produce energy.

Pressure reduction valves were first proposed to obtain optimal pressure values in water distribution networks with the benefit of reducing the amount of water leakage, as mentioned by several authors [23, 24, 25, 26, 27, 28, 29].

Among the discussion, several models and methods were proposed in order to obtain the optimal location of PRV's [30, 31]. And the replacement of PRV by micro hydro power plants has been proposed [32, 33, 34, 35].

Frequently, WDN are equipped with pumping systems and strategies for energy savings must be applied. These are based on an upgrade of hydraulic and electric machines efficiency, if under variable conditions variable frequency drivers must be used, to increase system performance while decreasing the used energy from the network [36, 37, 38].

A pump adds a certain energy to the flow, in order to promote the pumping of the fluid. When this does not occur, it leads to a reverse rotation of the wheel and therefore to a change in the direction of the flow, from the discharge location to the suction extreme. This transformation is denominated PAT (Pump as a Turbine). If the energy in pressure (head) is high enough to overcome the breakaway torque of the impeller and shaft, that torque can be used to drive a generator [41].

Thus PAT's could be used instead of classic turbines because they can promote a viable and flexible solution for energy production in a WDN due to their lower cost, flexibility for different sites and acceptable efficiency [22, 42, 43, 44].

Water distribution networks can contribute to a sustainable development because they are an essential part of energy use and hydraulic efficiency. When possible WDN can be incorporated into power generating systems, for example in micro-hydric installations (<100kW) and mini-hydric (100kW - 1MW). The incorporation will reduce the external dependence on energy, by re-use the pre-existing system components.

In water transmission/distribution systems the hydropower production is already a reality in a micro or mini scale when a large and constant hydraulic power is available. This kind of energy production has an economic benefit with a small environmental impact since there is an optimization of the pre-existing infrastructures [45].

2.5 Electrical Drive

Induction machines are used to generate approximately one third of the electrical energy worldwide and are one of the most used choices in micro-hydro stations [46].

However, induction machines can act as a motor or as a generator, depending on whether the shaft power is being put into the machine (generator) or taken out (motor). When working as a motor, the rotor spins a little slower than the synchronous speed established by the field windings, in an attempt to catch up the power delivered to the rotating shaft. On the other hand, as a generator, the turbine blades make the rotor spin faster than the synchronous speed and energy delivered to the stationary field windings [47].

Hydro and wind power generation are similar because in both cases their operation follows Bernoulli's Law for fluids in motion. Hydro and wind turbines can operate either in fixed or variable speeds. In fixed-speed turbines the technology is based in a constant-speed mechanical input.

Most of the times hydro and wind turbines are designed for a certain fluid speed at which the maximum efficiency can be achieved, and in both cases a regulator is needed. For this reason, topologies used for wind energy conversion can be applied in hydro-power production [48].

To obtain the best efficiency when connecting a small generator to the main grid, power electronics and digital controls must be used, figure 2.24.

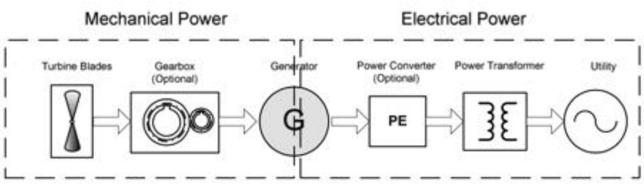


Figure 2.24: Main Components of hydropower generation, adapted from [49]

Some possible configurations of hydro turbines (valid for wind turbines) are:

1. Fixed-speed turbine with an induction generator;
2. Variable-speed turbine with a doubly-fed induction generator;
3. Variable-speed turbine with a synchronous generator.

(1) Fixed-speed with an induction generator:

Induction generators are specially used in systems without power electronics. The turbine spins the rotor shaft of a squirrel cage-rotor induction generator connected directly to the grid and the operation speed is almost constant. Induction machines require reactive power, which can be supplied by the grid network or by capacitors connected to the machine terminals. These machines do not deliver any reactive power, and sometimes require a soft-starter to reduce current inrush during start-up [50], see figure 2.25.

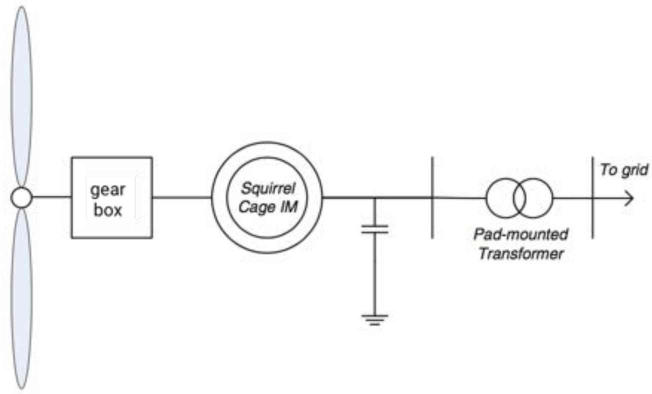


Figure 2.25: Fixed-Speed Turbine, with an induction generator, adapted from [51]

(2) Variable-speed with a doubly-fed induction generator:

The control of both active and reactive power requires e.g. wound-rotor induction machine, with both rotor and stator windings accessible. Power from the spinning rotor (at slip frequency) is collected through slip rings. Output power of the generator is passed through power electronics rectifier and inverter system, transforming the variable frequency into grid compatible AC power (with the proper voltage level and frequency). This configuration also needs a soft starter and reactive power compensation (using a capacitor bank) [50], see figure 2.26.

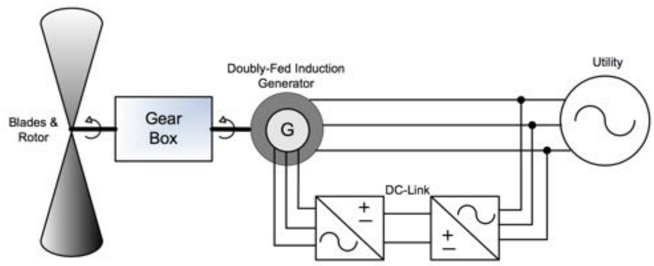


Figure 2.26: Variable-Speed Turbine, with a doubly-fed induction generator, adapted from [49]

(3) Variable-speed with a synchronous generator

This type of topology uses a conventional or permanent magnet synchronous generator to convert the hydro turbine power to a variable voltage and frequency. Frequency output will vary with the water passing through the blades. Power electronics based rectifier and inverter are used to convert the rated output of the machine to power compatible to the main network. This configuration has extra losses in power conversion, although the power gain will increase. In this configuration, the turbine can operate in a variable speed allowing a higher efficiency in energy conversion, see figure 2.27.

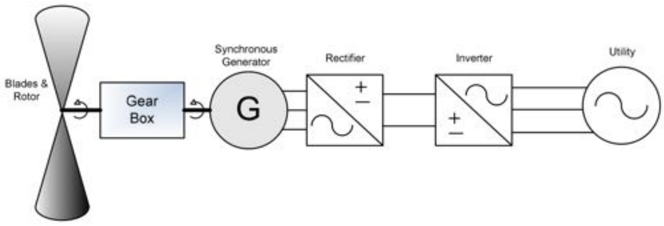


Figure 2.27: Variable-Speed Turbine, with a synchronous generator, adapted from [49]

Chapter 3

Experimental Setup

In this chapter the system design its elements will be presented. Along with the simulation results obtained with the an auxiliary software.

System design is specially important because it's possible to guarantee that the system is not underdeveloped or overdeveloped.

3.1 Design

The main purpose of water distribution networks is not energy production. However, the type of infrastructures and network used under normal operation (pressure reduction and flow control valves, reservoirs, pumps and the piping system) allows a full roll of possibilities for power generation scenarios while an almost constant flow is maintained (24h/day).

It is possible to generate energy in the points of the network where it is possible to replace a pressure reducing valve, by a PAT, because an increase in water demand will correspond to an increase in electrical power demand. The principle used for energy production can be extrapolated for water storage, in hours of lower demand, the water can be pumped between reservoirs, and be stored.

This study investigates the possibility of implementing an installation that will allow the development of techniques in a water distribution network leading to energy production, having the question as guide: "What are the real numbers of energy production in a WDN?".

The data and the simulation model later proposed are based on the work developed by [52], [53] and [54].

An experimental unit was created in the Electrical Department of FCT NOVA, to simulate and analyse the initial idea. For this propose all the designs were made in order to validate the material list. The experimental unit will be used in the future in order to help understand all the phenomena and concepts behind the energy production, in WDN.

The installation has a discharge reservoir where water is drained to the circuit through a pump, next an hydropneumatic reservoir or RCA (Reservoir of Compressed Air) to stabilize the output pressure of the pump. Then the PAT is tested. There are also measurement elements in the system in order to monitor flow and pressure. The detailed schematic is shown in figure 3.1.

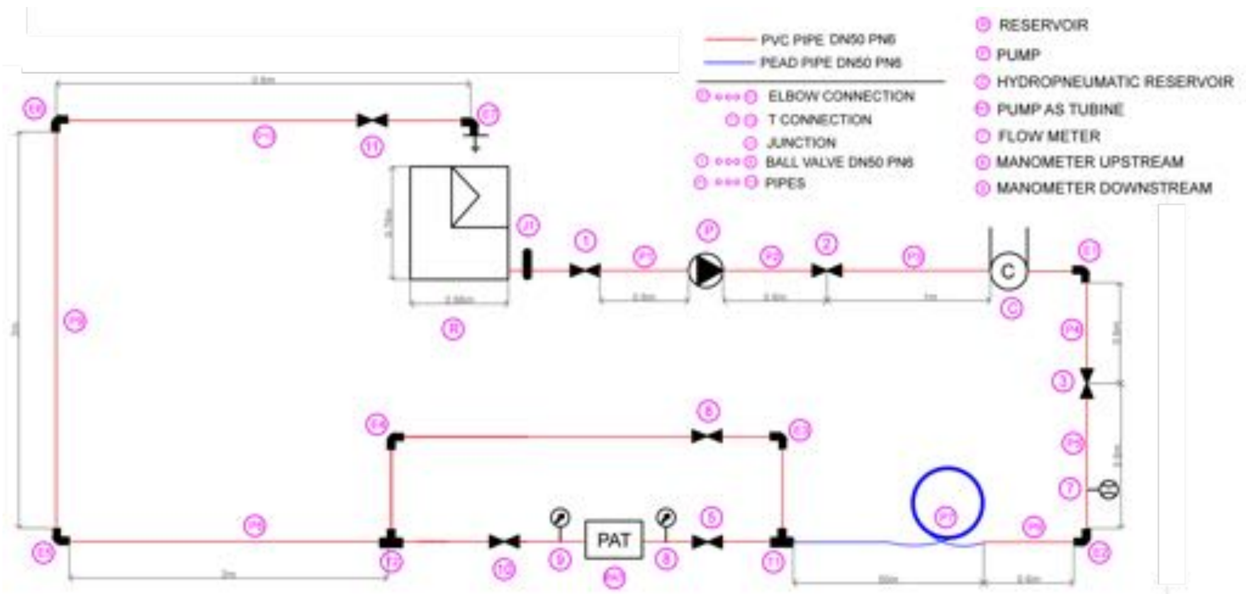


Figure 3.1: Design Experimental Unit

Only steady-state will be considered in this thesis. However, transient electrical and hydraulic analysis is extremely important in order to design appropriate electrical protection methods.

3.1.1 System Design Parameters

In order to start the design of the test rig some parameters were pre-defined. Selection of pumps, reservoir and measurements devices are dependent on the definition of such parameters.

The test rig intends to simulate the conditions of a water distribution network, as a way of verifying the possibility of energy production. Due to this fact the parameters of a WDN were assumed in the first place.

1. Type of water system: Clean water without waste;

2. Available head: 4 m;

3. Flow: 3.4 meters m/s;

4. Pipe diameter: DN50 (50 mm);

5. Maximum Pressure: PN10 (10 bar).

The pre-selected PAT has the operation point of (3.4 L/s, 4 m), which will be the design system point, it is equivalent to a site location in hydropower design where there is an available head and flow for energy production.

3.1.2 Pipe Design

In order to make the hydraulic design of the system it is necessary to consider the effect of dissipative forces, head losses. In this case, that will allow the calculation of the net head. The design net head, see equation 3.1, will be used to define the design output of a turbine, in this case the PAT (using the maximum power output for the best efficiency head).

$$H_0 = Z_u - Z_d - \sum_i \Delta H_i \tag{3.1}$$

where Z_u is the water level intake, Z_d is the water level tailace and ΔH_i are all the head losses, both variables are expressed in m.

There are also losses along pipes (friction head losses and singular losses). It is possible to assess the effect of losses in pressure drop after their calculation. The type of loss depends on pipe topology. In a closed pressurized system the velocity is high enough to ensure uniform turbulent flow. So in this situation the flow type is turbulent (Re > 2,000) and Colebrook-White formula (explained ahead) must be used for friction head loss calculation, with an iterative method to solve the friction factor for each discharge value. However, Moody diagram allows a graphical calculation knowing: V (mean velocity), D diameter, k_r absolute roughness and ν kinematic viscosity of water.

Flow losses will increase with the square of flow velocity. And the flow loss is given by the sum of constituent pipelines parts friction loss and local losses from all components and fittings.

- **Friction head loss**

As presented before, Bernoulli's equation allows the calculation of a fluid flow. The equation uses as principle the first law of thermodynamics (*the energy in an isolated system is constant; energy can be transformed but never destroyed*) and it calculates the energy balance of an incompressible flow in steady state. Equation 3.2 is the general equation for head losses, in circular pipes.

$$h_L = \Delta\left(\frac{p}{\rho} + z + \frac{V^2}{2g}\right) \tag{3.2}$$

where h_L is the head loss, expressed in m; p is the pressure drop, expressed in Pa; z is the pipe elevation, expressed in m; V the average flow velocity, expressed in m/s; g is the acceleration of gravity, expressed in m/s^2.

Along a canal or a penstock the friction loss is expressed by equation 3.3, with J being the hydraulic gradient and L the length of the canal or penstock, expressed in m. Using equation 3.3 and Darcy-Weisbach factor (equation 3.4) it is possible to define the friction head loss equation 3.5.

$$\Delta H_r = JL \tag{3.3}$$

$$f = \frac{JD_{int}}{V^2/2g} \tag{3.4}$$

$$h_r = f\frac{L}{D_{int}\frac{V^2}{2g}} \tag{3.5}$$

Mean velocity (V) is defined as the average velocity of flow across a section (determined by the continuity equation for steady state flow). It is expressed as a ratio between volumetric flow rate (Q) m^3/s and radius-sectional inlet section (S_{inlet}) m^2 of the pipe, as shown in equation 3.6. The cross section in the pipe is defined by equation 3.7. The inlet diameter of a pipe is calculated using the thickness of the pipe (e), see figure 3.2 and equation 3.8.

$$V = \frac{Q}{S_{inlet}} \tag{3.6}$$

$$S_{inlet} = \pi r^2 = \frac{\pi D_{inlet}^2}{4} \tag{3.7}$$

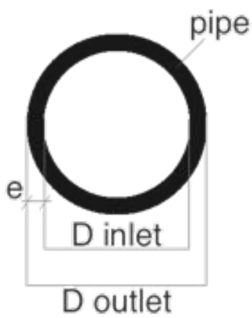


Figure 3.2: Calculation of inlet diameter

$$D_{inlet} = D_{outlet} - 2e \tag{3.8}$$

Colebrook-White formula

As mentioned before, the design formula for turbulent friction is expressed by Colebrook White formula 3.9 in which ϵ represents the wall absolute roughness, equation 3.10 is the relative roughness ratio. This ratio indicates the roughness ratio of a pipe or tube; an high value of this ratio indicates a larger friction factor that leads to an higher pressure drop. Roughness ratio can be calculated using Moody's Diagram, see figure3.3, or the recommended table values (table 3.1).

$$\frac{1}{f^{1/2}} = -2\log\left(\frac{\epsilon/d}{3.7} + \frac{2.51}{Re_d f^{1/2}}\right) \tag{3.9}$$

$$k_r = \frac{\epsilon}{D}[mm] \tag{3.10}$$

$$Re = \frac{VD}{\nu} \tag{3.11}$$

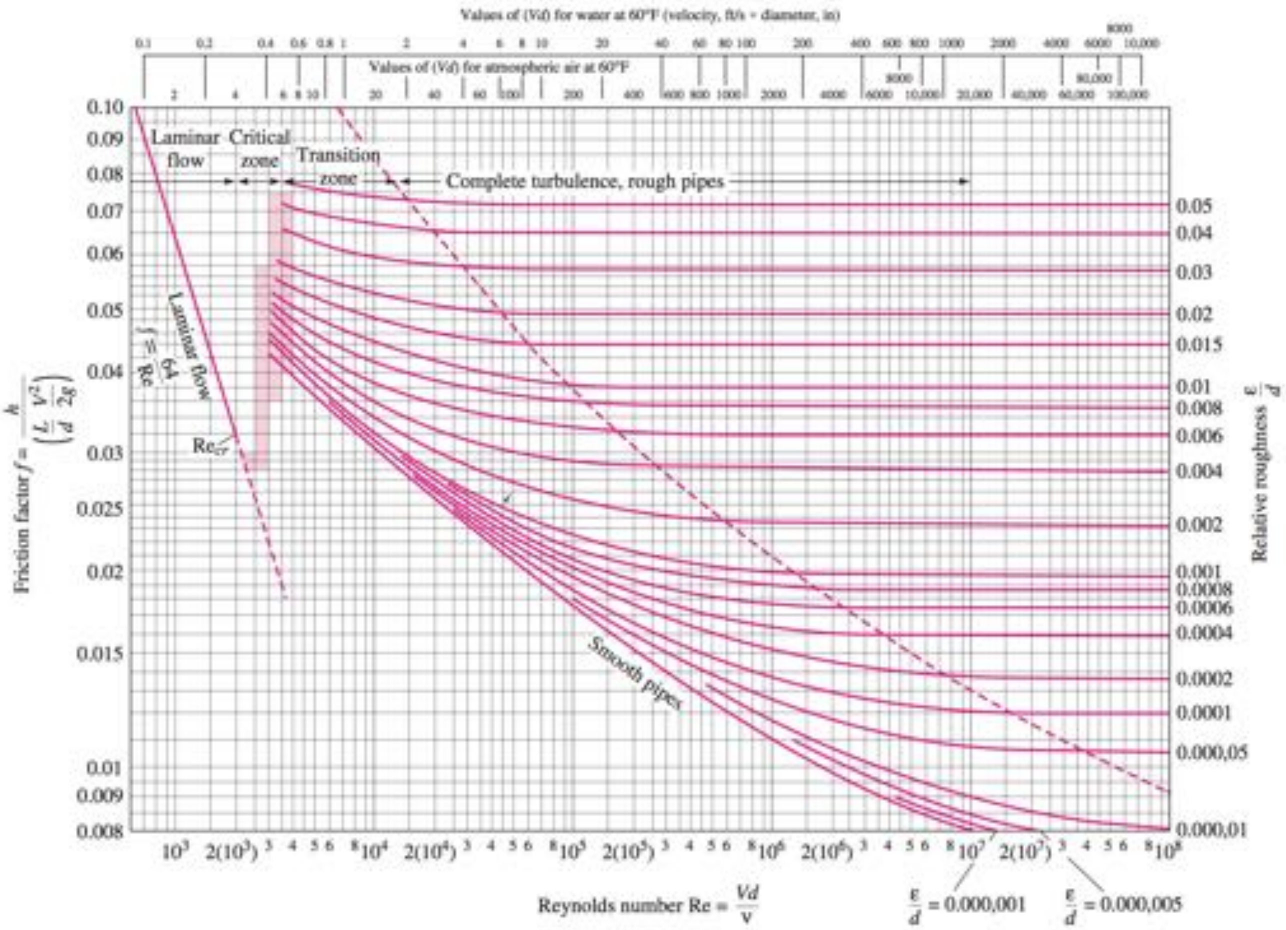


Figure 3.3: Moody Diagram

Singular or Local losses

Previous equations and formulas do not encompass all the losses in single elements of the network (contractions, expansions, bends, tees, gates and valves). These elements

Table 3.1: Surface roughness (k) for pipes

Pipe material	**New pipe** k (mm)	**Old pipe** k (mm)
plastic	0.01	0.25
drawn steel	0.05	1.0
welded steel	0.1	1.0
drawn stainless steel	0.05	0.25
welded stainless steel	0.1	0.25
cast iron	0.25	1.0
galvanizes steel	0.15	

cause additional losses that compromise both friction and turbulent components. The generic equation for single head loss can be calculated using equation 3.12, ζ is the coefficient of singular loss that depends on the geometry of the singularity of the network and Reynolds number. Each element of the network will have a specific value for single loss, table 3.3 and appendix I. Usually, the values, specially for valves, are determined experimentally and the data must be provided by manufactures. It is important to note that friction loss of these elements are not included in the local resistance factor, instead this factor is calculated as a part of the main friction loss by including their length and diameter when calculating the pipeline length.

$$h_s = \zeta \frac{V^2}{2g} \tag{3.12}$$

where, V is the velocity and g is the gravity acceleration.

Table 3.2: Pipe Bend: Local losses coefficient ζ

Element	ζ
Pipe Bend 90, R/D=1.5	0.3
Discharge Loss	1 (pipe without expansion)
Swing Check Valve	1....2
Ball Check Valve	0.7 ... 1.2
Gate Valve	0.2

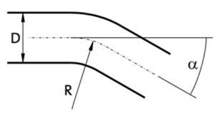
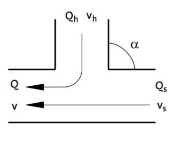


Table 3.3: Tee: Local losses coefficient ζ

Tee	Q_h/Q	$\alpha = 90$	
		ζ_s	ζ_h
	0.8	0.72	0.51
	1.0	0.91	0.6



However, in order to determine the pipe length for a certain pipe diameter, pump power and flow rate, the pump head must match the piping head loss. Ignoring minor losses, pipe length follows Darcy's formula 3.13. Q, d, ϵ are known parameters that allow the computation of Re_d and f. Pump efficiency will vary according to the flow rate, so pipe length must match the pump's region of maximum efficiency.

$$h_{pump} = \frac{Power}{\rho g Q} = h_f = f \frac{L}{d} \frac{V^2}{2g} \tag{3.13}$$

There are two types of measurement units commonly used for pipelines, inches and millimetres, table 3.4.

Table 3.4: Nominal diameters millimetres vs inches

DN	
mm	in
25	1”
32	1 1/4”
40	1 1/2”
50	2”

Using the system design presented in figure3.1, total head loss is 5.6 meters, table 3.5.

Table 3.5: Total Head loss

Type of loss	**Value**
Regular	2.9 m
Singular	2.7 m
TOTAL	5.6 m

3.1.3 Machines Design: PAT and Pump

As described before, the PAT was pre-selected in order to have the operation point (3.4 L/s, 4 m), given by pump curve, figure 3.4 and annex IV. Although, to design the initial pump (responsible for the water circulation through the pipelines) it was necessary to consider a pump curve having as guide principle the pipe head loss, the pump selection must correspond to at least a 10 meters head, because of the sum head loss of plus 4 meters head loss of PAT.

In order to achieve the requirements, a pump with a maximum of 20 meters head was pre-selected, figure 3.5 (Curve C) and annex V.

Information about the selected induction machine can be found in annexVI.

Combining the characteristics curves from PAT and pump, and assuming the initial operation point, it is possible to understand that the system is quite over designed, figure 3.6. Although, choosing a pump above the operation point ensures that, in the worst case, if new elements were added to the network, or if the type of material and fittings changed from the design, the system kept its initial efficiency.

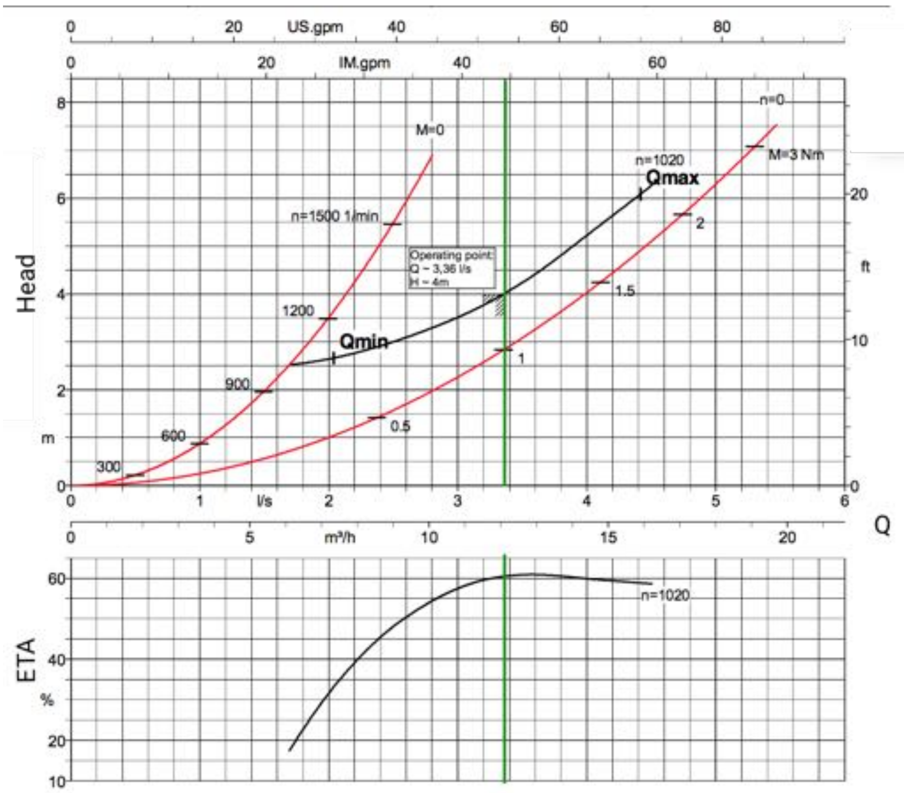


Figure 3.4: PAT Curve

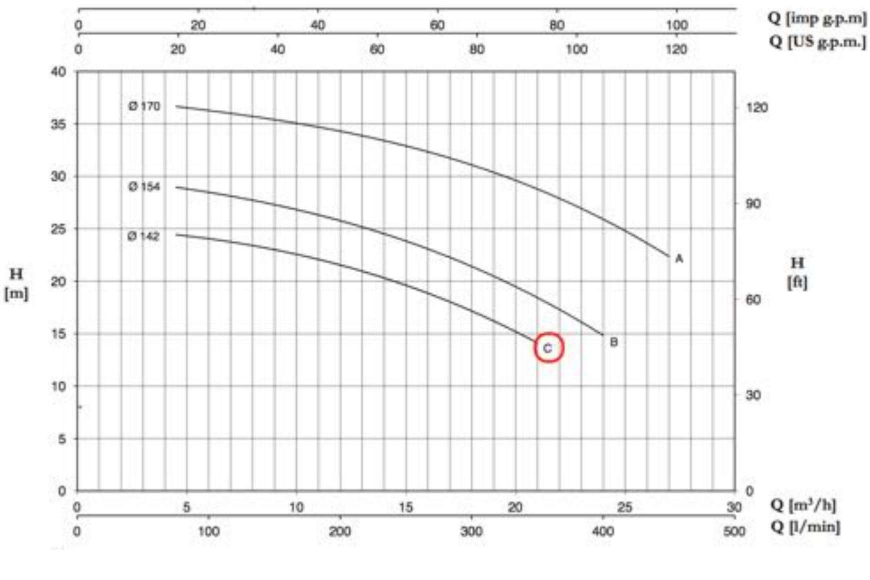


Figure 3.5: *Pump:* Characteristic Curve C

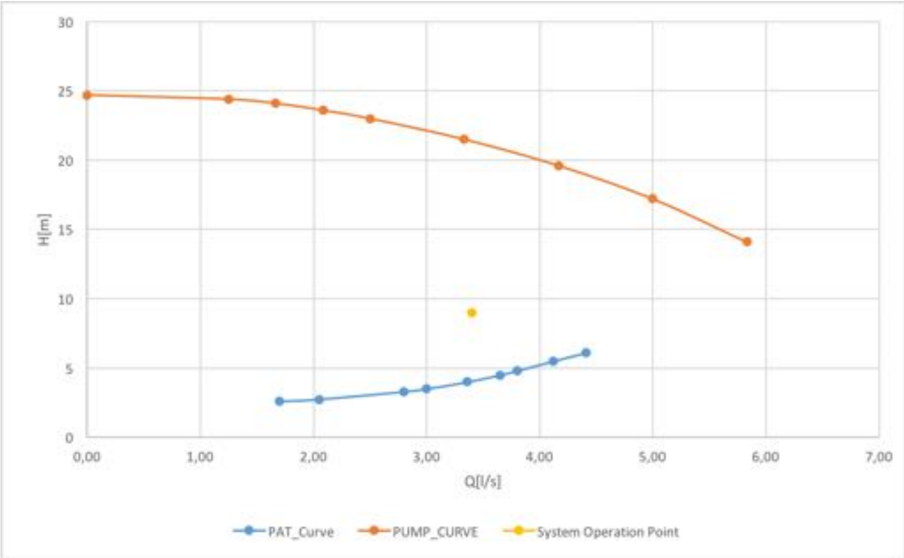


Figure 3.6: Pump Curve, PAT and system operation point

3.1.4 Reservoirs

In this work two different types of reservoirs were used: a storage reservoir with the possibility of discharge and a hydropneumatic reservoir.

- **Storage/Discharge**

Storage/discharge reservoirs do not have any particular specification, the only requirement was to have enough volume for water storage as well as ensure a discharge point in the system. Using the operation point of (3.4 L/s, 4 m), if the system works for at least 5 minutes, the reservoir must have a capacity of 300 liters of water assuring supply without interruptions, see figure 3.7.

Figure 3.7: Reservoir Example

- **Hydropneumatic Reservoir**

In a pipeline system a fault can lead to an increase (overpressure) or a decrease (depression) in pressure, resulting in a sudden modification of flow characteristics, leading to a transient regime. This is specially important in lifting pressurized conduits due to the possible stop of pumping group, power shut down or by an unexpected closure of a safety valve.

The stopping action will cause a negative pressure wave that propagates from the pumping group till the downstream of the reservoir, at a constant speed. When the propagated wave reaches the reservoir, a positive pressure wave will propagate in the opposite direction reaching the pump again. This phenomenon can cause several problems such as conduit rupture, in the overpressure phase (due to the passing of nominal pipelines pressure).

It is important to have devices in the network that prevent this effect: there are several types of protection devices such as hydropneumatic reservoirs, suction valves, inertia flywheels coupled to the drive shaft of the pumping unit and equilibrium stacks.

Hydropneumatic reservoirs are particularly important in the system protection, protecting systems against shock waves. These reservoirs have a close chamber that contained water and compress air, with pressure equal to the steady state operation. They are connected to the conduit (figure 3.8), if an overpressure occurs the conduit is feed, in case of a depression, the reservoir is fed by the system, figure 3.9.

The operation principle of these reservoirs makes them a possible solution against pressure variations. There are two main types of hydropneumatic reservoirs: the ones with membrane and preload (if necessary) and without membrane and preload using external compressed air.

In this study, a 100 liter and 10 bar hydraulic reservoir is enough because the system maximum pressure is no more than 10 bar. An example is presented in figure 3.10.

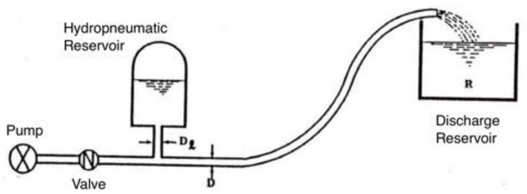


Figure 3.8: System connection

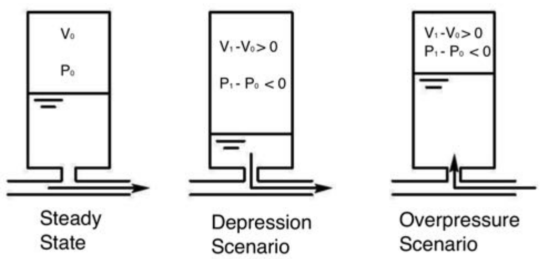


Figure 3.9: Possible operation scenarios

Figure 3.10: Hydropneumatic reservoir

3.1.5 Measurement Devices

Two types of measurement devices were considered in the system, namely a manometer and a flow meter.

- **Manometer**

A manometer is a device for measuring pressure in closed systems, which uses a column of liquid. This type of device measures the difference between atmospheric and the pressure inside a close system.

Precision of this device will be influenced by the density of the liquid.

The scale of this measurement device will be influenced by the system maximum pressure, as a way to assure a better resolution as possible.

In this case, the scale must be between 6 bar and 10 bar due to system nominal pressure (examples of manometers figure 3.11).

Figure 3.11: Manometers example: with and without glycerine

- **Flow Meter**

In order to choose a flow meter, the main requirement is permanent flow. In this study, as described before, the operation point is (3.4 L/s, 4 m). It is thus necessary to have a flow meter that in a permanent operation measures a flow of 3.4 L/s which is equal to 12.24 m^3/h; an example of a flow meter is shown in figure 3.12

Figure 3.12: Flow meter, from Resopre-Janz Company

In order to obtain a digital measurement of flow, an Arduino Uno and an inductive sensor were used. This is a sensor that, at each complete rotation of the main flow meter, sent a digital impulse, each impulse is equal to 10 liters.

This value will be measured by Arduino, since the type of impulse generated by inductive sensor is digital (active high). A pull-down resistor circuit (figure 3.13) is connected to inductive sensor terminals. Each time a pulse is sent by the inductive generator switch closed and that value will be read by Arduino Uno.

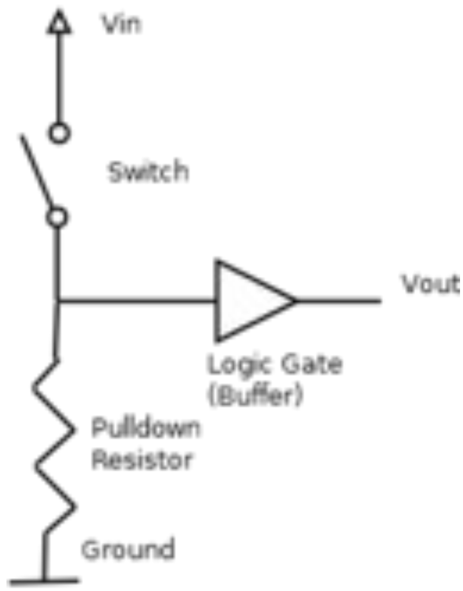


Figure 3.13: Pull-Down Resistor

3.2 Computational Design: EPANET

In order to support the system design an auxiliary software was used, namely EPANET.

EPANET is a software that models water distribution networks. This software allows the definition of all network elements, such as reservoirs, pipes, fittings and pumps. Moreover, it allows computing losses (singular and regular) and calculate pressure and flow along the system, among with other variables.

After the setup of the system elements (annex III), computational simulation results can be obtained, from both pressure (figure 3.14) and flow (figure 3.15); the scale colours indicates the different values.

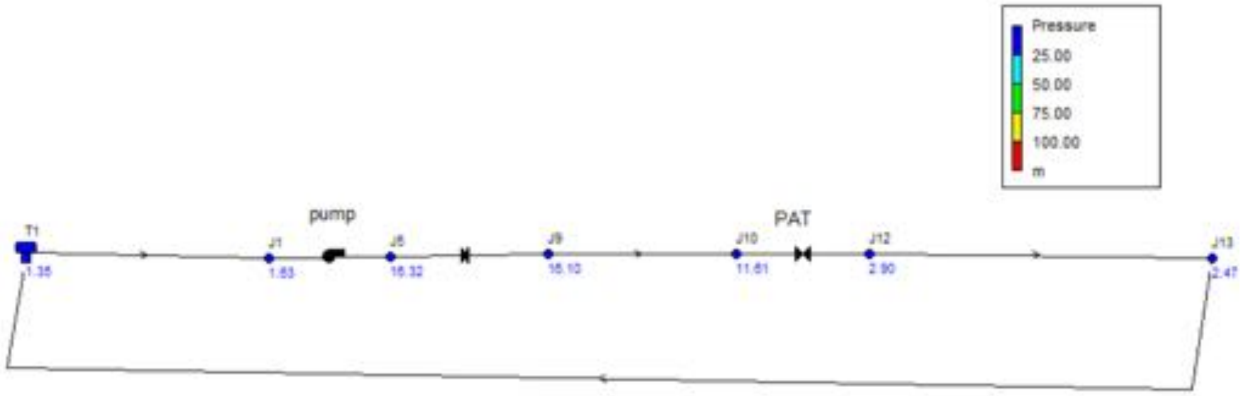


Figure 3.14: *EPANET:* Simulation of system pressure (P<25m)

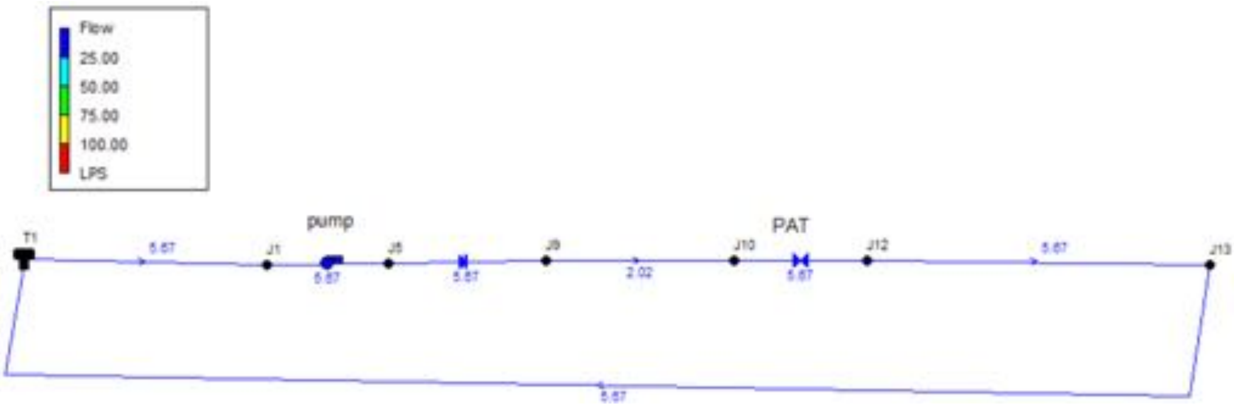


Figure 3.15: *EPANET:* Simulation of system flow (Q<25l/s)

In this case, it is possible to understand that a PAT in a WDN leads to a pressure drop, as shown in figure 3.14). This data supports all the design of this experimental setup, making possible to recover energy from a WDN by pressure reduction. However, it is necessary to prove this concept using the experimental setup.

Figure 3.15 presents the flow in an ideal system, proposed by this study and is possible to observe that the flow value is the same in all system.

Chapter 4

Material Selection and Implementation

After the design of the network elements, the material was carefully selected, as presented in the next section. A correct choice can lead to a higher efficiency due to the losses and leakages reduction but also to decrease installation costs.

System implementation methods are also presented, a proper procedure will assure no mismatch and leakages in the system.

4.1 Material Selection

4.1.1 Pipes

After the design, the chosen pipe material was PEAD and PVC, with a nominal diameter of 50 and 40 millimetres (DN50 and DN40), respectively, based on the main advantages and disadvantages of each material type, see table 4.1. PEAD pipes is a type of rigid plastic suitable for network branches without a change in direction. On the other hand, PVC can be used in places were an extreme direction change is needed.

Table 4.1: Pipe materials: Advantages and disadvantages

Material	Advantages	Disadvantages
Metal	- High pressure and temperature resistance; -Durability; Shock Resistance.	- High Pressure Losses; Hardly Handling; - Corrosion; -Construction of flat branches and networks.
Plastic (Flexible)	-Easy handling; -Light weight; -Small head losses; -Construction of non linear branches and networks.	-Low pressure and temperature resistance; -Affected by UV radiation.
Plastic (Rigid)	-Easy handling; -Light weight.	-High head losses -Construction of flat branches and networks.

4.1.2 Fittings

Fittings are used whenever a connection of two or more elements is needed, in a network. These can be made of different materials, depending on the network configuration and specifications. Proposed design assume all fittings were DN50, although after its review, fittings range from DN5O to DN32.

Table 4.2 resume selected fittings and their main function.

Table 4.2: Fitting Types

	Fitting Name	Material/ Diameter	Description
	Brass Deposit Canon	Brass 1” 1/2	To make the connection between Discharge Reservoir and the system
	Ball Valve	Brass f/f 1”1/2	To isolate parts of the system network
	Male Adaptor	PEAD 50 x 1”1/2	To make the connection between fittings and pipes
	Elbow	Brass m/f 1”1/2	To make a smooth direction change
	Tee: Type 1	PEAD 50x 1 1/2”	To create a point of derivation and reduce the nominal diameter in one side
	Tee: Type 2	Brass 1 1/2”	To create a point of derivation
	Tee: Type 3	Brass 1”1/2 x 3/4	To create a point of derivation and reduce the nominal diameter in one side
	Double Male Bushing	Brass 2” x 1 1/2” 1 1/2” x 1 1/4”	To fixe elements (two sides)
	Reducing Nut	Brass 2” x 1 1/2” 2” x 1 1/4” 3/4” x 1/2”	To fix elements (one side)
	Union	Brass 1 1/2”	To connect to male/female elements
	Flange	Inox 2”	To connect to elements while maintaining a compress force, to seal the connection.

4.1.3 Pump and PAT

The selected circulation pump was a monobloc horizontal centrifugal pump, see figure4.1, for a maximum pressure of 10 bar. This pump will impose a flow in the sytem that will be used for power generation, simulationg a water distribution network flow. This pump was by Caprari company and was equipped with a 2 pole induction motor. Detailed information about the motor is presented in table 4.3.

Figure 4.1: Circulation Pump

Table 4.3: Circulation Pump: Characteristics

Company	Caprari
Model	CM32-16C
Q (m^3/h)	4.5 - 21
H (m)	24.4 - 14.1
H min (m)	14.1
H max (m)	24.7
HP	2
kW	1.5
U Δ	220 - 240
U star	380 - 415
I (A)	4
f (Hz)	50
N (RPM)	2900
AC	3 phase

The pre-selected PAT was an horizontal, single-stage pump, working as a turbine, see figure 4.2 and table 4.4 for detailed hydraulic characteristics, manufactured by KSB company. This machine was equipped with a squirrel cage induction machine, characteristics in table 4.5.

Figure 4.2: Pump as a turbine (PAT)

Table 4.4: PAT: Hydraulic characteristics

Company	KSB
Model	Etanorm 50-32-125
(mm)	139
Q (m3/h)	12.24
H (m)	3.69
N (RPM)	1020

Table 4.5: PAT: Electric Characteristics

Company	Siemens
Model	3 MOT1LA7083-6AA10-Z
P (kW)	0.55
U delta	230
U star	400
I (A)	2.8 / 1.59
cos(φ)	0.74
N (RPM)	910
η (%)	67.5

4.1.3.1 Discharge and Hydropneumatic Reservoirs

As described before, the system has two reservoir types with different purposes. One for discharge and other to protect against faults and to provide a constant pressure along the system (hydraulic reservoir).

- **Discharge Reservoir**

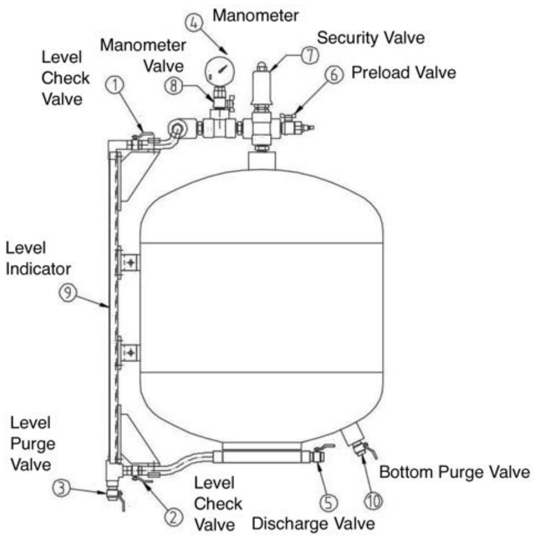
The discharge reservoir is made of fibreglass has a maximum capacity of 250 liters, and was able to supply water for the system, see figure 4.3, moreover that was also the system discharge point, for its kind there is a wide range of products available in the market, for this study it was manufactured by Momel S.A. company.

Figure 4.3: Initial reservoir of 250 L capacity

- **Hydropneumatic Reservoir**

An hydropneumatic reservoir with 100 L equipped with membrane was chosen, with an inlet / outlet diameter of 50 mm (DN50), a nominal pressure of 10 bar (PN 10) and without preload, intended to solve the problems resulting from hydraulic shock caused by a sudden stop of the pump maintain a constant system pressure. The selected hydropnemautic reservoir was manufactured by Henriques e Henriques company, see figure 4.4.

(a) Hydropneumatic reservoir



(b) Components

Figure 4.4: Hydropneumatic reservoir and components

4.1.4 Measurement Instruments

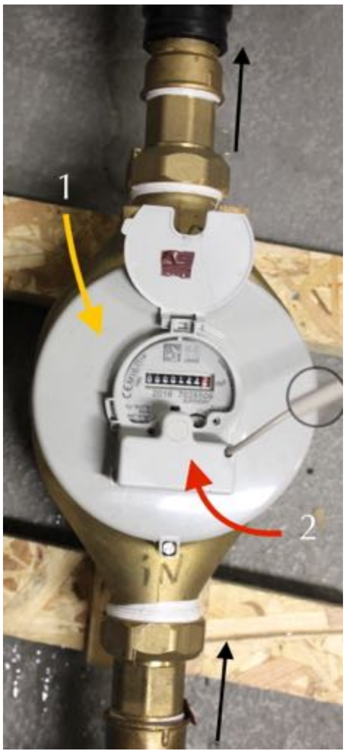
- **Manometer**

The chosen manometer has a maximum scale of 6 bar and was liquid-filled with glycerol. Glycerol allows the life of the appliance to be longer, since in case of sudden pressure reduction or high vibrations the liquid-filled manometer has no influence from external factors.

To measure the pressure at downstream and upstream of the PAT a manometer was selected. It has a maximum scale of 6 bar and was liquid-filled with glycerol; being liquid filled with glycerol is possible to guarantee that the measured value was not influenced by external factors, see figure 4.5.

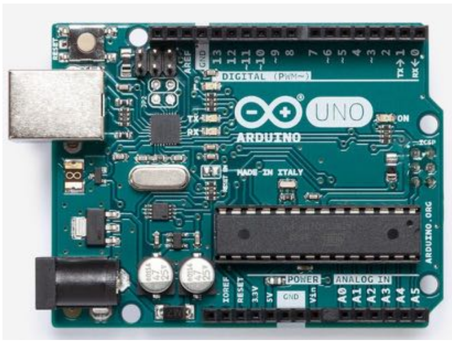
Figure 4.5: Manometer

- **Flow meter**



(a) 1- flow meter, 2- inductive sensor

(b) Flow meter characteristics



(c) Arduino Uno

Figure 4.6: Flow meter

In this case it will be used a volumetric flow meter with an inductive sensor for the pulse measurement, see figure 4.6. The main advantages of this type of flow meter when compared with equivalent solutions are the technology widely used, measures are not affected by the velocity profile neither external influences and the required installation space is small. There is also an wide variety of models, features and pricing. The main disadvantage is the vibration effects at high flow rates.

Flow meter main characteristics were a DN40 nominal diameter and permanent flow of Q = 16 m^3/h, see figure 4.6b.

In order to get a digital flow value, an Arduino Uno 4.6c was used. Table 4.6 presents output values for the used inductive sensor. This means that after passing 10 liters through the flow meter an impulse will be sent to Arduino Uno, see figure 4.6c.

Table 4.6: Inductive Sensor

Model	Input	Output	Conversion
JV400 Q3=16	1 pulse	1 pulse	10 L
	10 pulses		100 L
	100 pulses		1000 L

- **Electrical Devices**

An energy analyser was used to confirm the power flow, figure 4.7, and an autotransformer was used to regulate voltage level in circulation pump terminals, figure 4.8.

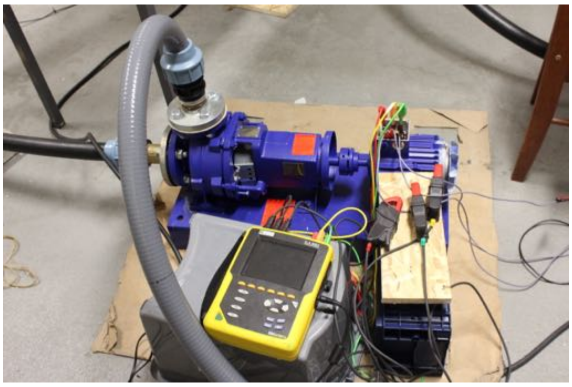


Figure 4.7: Energy Analyser

(a) 3 phase autotransformer used for circulation pump

(b) 3 phase autotransformer for PAT

Figure 4.8: Autotransformer's

4.2 Implementation

The experimental setup intends to simulate a water distribution network under specific conditions. In order to achieve this goal two different phases must be considered. The test rig plays an important role because without the creation of this unit it was not possible to guarantee such conditions. The first phase is regarding to material assembly and phase two is related to experimental measurements.

This project arises from the need to test a PAT energy efficiency when inserted into a water distribution network as an energy source. To materialize this concept it was necessary to select, purchase and assemble all the elements. Several manufactures were consulted to find the best market solutions with the shortest delivery time.

- **Security**

One of the main concerns in this work was security; during the test ring construction and the preparation for simulation (phase one) a special caution was taken, since heavy tools and an electrical saw were used; its proper use and selection prevent major accidents.

In experimental measurements (phase two), security requirements were extremely high, not only because the system was under pressure, but also because of the voltage level ($400V$), an high enough voltage to injure a person or even cause death so all security protocols were followed and protection against faults was considered.

- **Phase One:** Material assembly

Phase one was the phase were all elements were connected from its unit stage state through the final configuration. It was specially important to follow a defined order of material assembly, to avoid matching conflicts.

In figure 4.9 a draft is presented, the system assembly must start with the element with the red arrow behind (discharge reservoir).

1. The discharge reservoir must be the first assemble element;
2. Make a hole, in the discharge reservoir, using a cranial drill;
3. Install a brass deposit cannon, an element which allows the connection with the system, figure 4.10;
4. Connect a ball Valve, using teflon to prevent leaks since the connection is between two metal elements;
5. Connect the pipes, using a male adaptor figure 4.11;
6. PVC and PEAD pipes measurement and cut;
7. Assembly of male adaptor, e.g. figure 4.12:

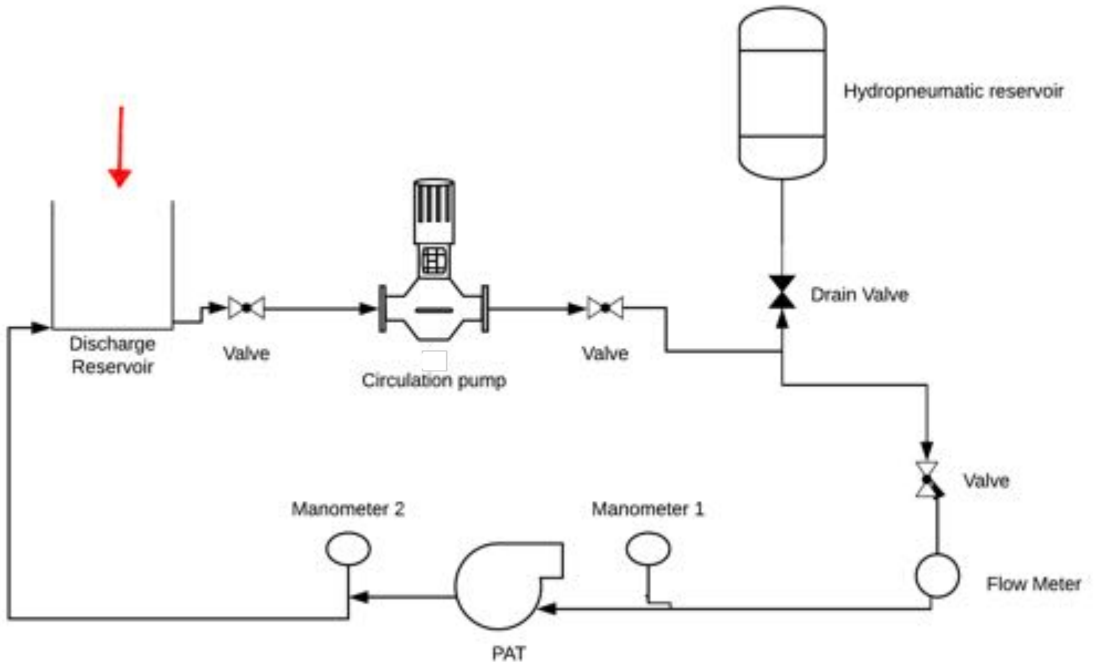


Figure 4.9: Assembly Draft

a) Place the cap nut into the pipeline;

b) Push the clinching ring nearby to the end nut;

c) Make the blocking bush pass through the pipe;

d) Lubrificate the o-ring to prevent damage during the installation and incorrect water insulation;

e) Place the pipe in the fitting body (must be used some force);

f) Screw the end cap into the body;

g) When necessary to make a transition from an accessory to pipes use a male adapter.

8. Pump Installation;

   a) Assemble a reducing nut in the initial pump inlet and outlet;

   b) Repeat 7;

   c) Connect an elbow with the outlet reducing nut, figure 4.13;

   d) Hydropneumatic reservoir, figure 4.14:

9. Hydropneumatic Reservoir

   a) Place an insulation ring between flange and hydropneumatic reservoir;

   b) Fix flange using M16 hexagon head screw;

c) Use a reducing nut and a double male bushing to connect an element, apply some teflon in the elements;

d) Assemble the ball valve;

e) Assemble other double male bushing and an Union;

f) Repeat 7 to female adaptor connection.

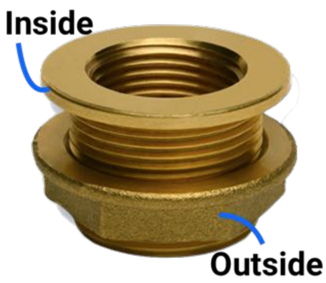


Figure 4.10: Brass deposit cannon

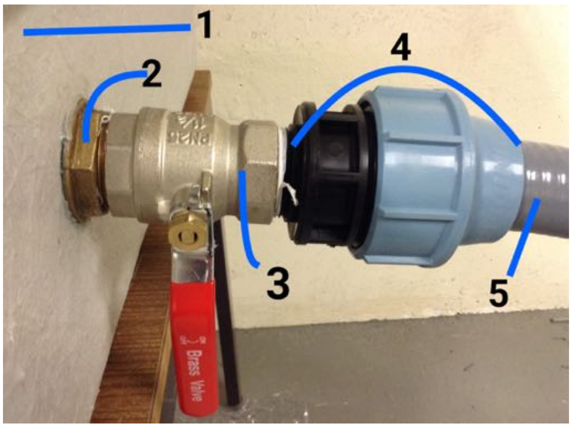


Figure 4.11: *Reservoir exit:* 1. Discharge reservoir, 2. Brass deposit cannon, 3. Ball valve, 4. Male adaptor, 5. Pipe

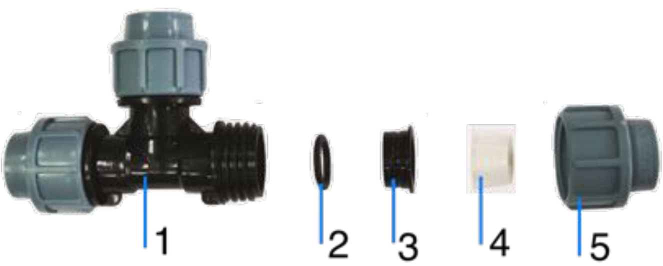


Figure 4.12: Fitting constitution - 1. Body, 2. O-ring, 3. Blocking bush, 4. Clinching ring, 5. Cap nut

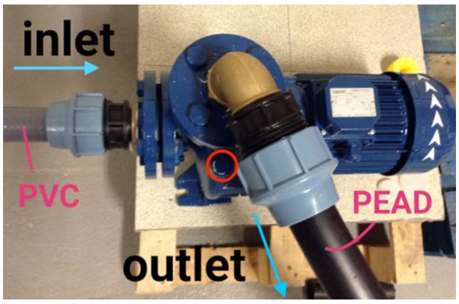


Figure 4.13: *Initial pump:* Inlet, outlet and pipe material

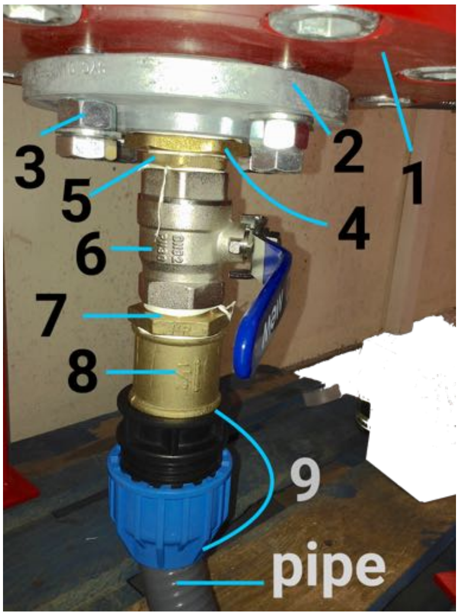


Figure 4.14: *Hdropneumatic reservoir exit:* 1. Hydropneumatic reservoir, 2. Flange DN65, 3. M16 hexagon head screw, 4. Reducing nut, 5. Double male bushing, 6. Ball valve, 7. Double male bushing, 8. Female union, 9. Female adaptor

1. Repeat 7 to tee connection;
2. Assemble the flow meter, using sequence 7, to connect the adaptors, and follow the installation instructions (caution with the flow direction) 4.15;
3. Assemble the brass tee (exit for PAT and bypass) and a ball valve to its terminals (when one is open, the other must be close), use teflon and horse hair;
4. Assemble a brass and reducing tee, use Teflon;
5. Place manometer, PAT path, figure4.16;

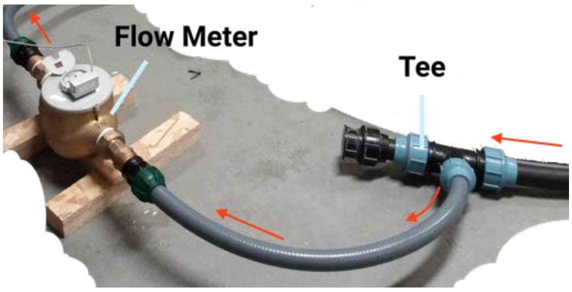


Figure 4.15: *Flow Meter Installation*

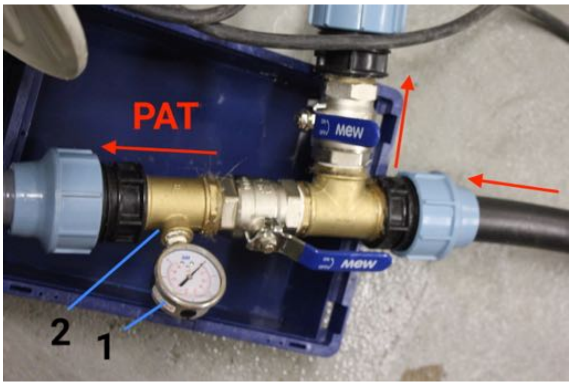


Figure 4.16: *Manometer installation*

1. Repeat 7;
2. Place a reducing tee at the inlet and outlet of the pump, use Teflon;
3. Repeat 7 (x2);
4. Assemble double male reducing bushing, use some teflon and horse hair (2x), this step must be followed for PAT inlet and outlet, figure 4.17;
5. Assemble an Union for male adaptor connection, figure 4.17;

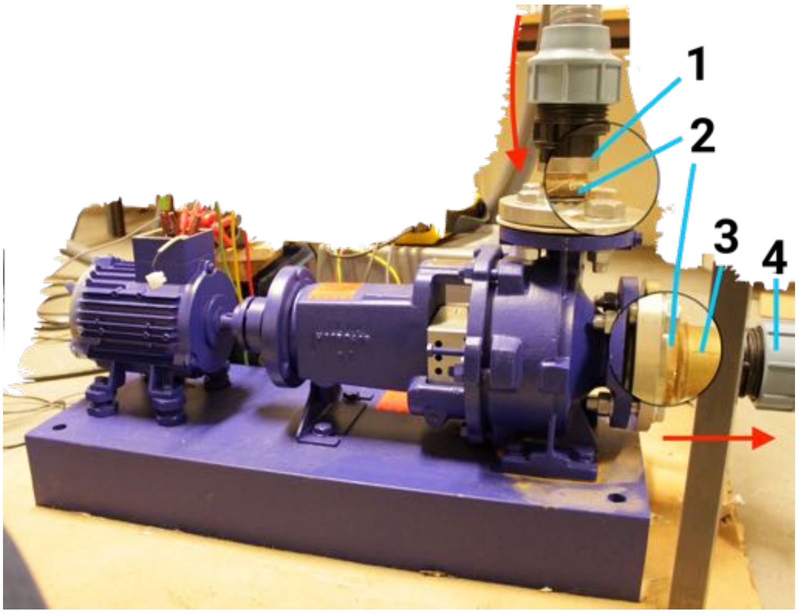


Figure 4.17: *PAT: 1. Female adaptor, 2. Double male reducing bushing, 3. union, 4. Male adaptor*

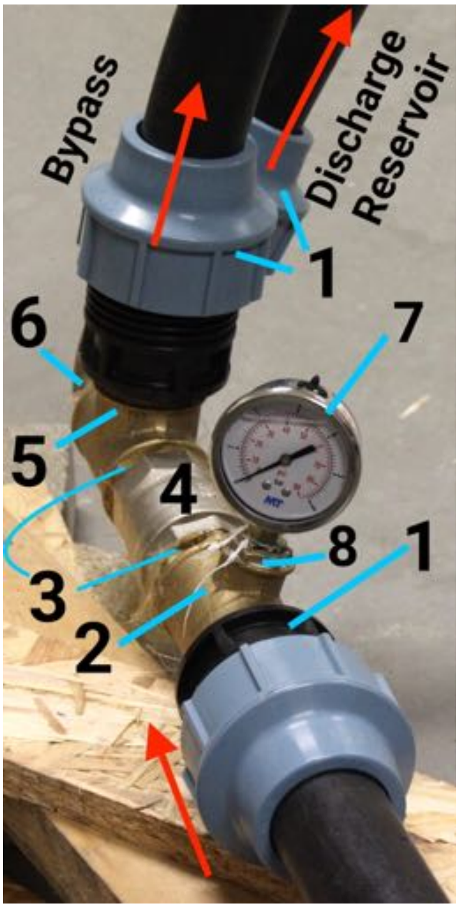


Figure 4.18: *PAT: 1. Female adaptor, 2. Reducing tee, 3. Reducing nut, 4. Ball valve, 5. Tee, 6. Elbow, 7. Manometer, 8. Reducing nut*

1. Repeat 7;
2. Assemble the reducing tee, two reducing nuts (to match manometer diameter), use teflon between the elements;
3. Assemble the reducing nut;
4. Place the ball valve;
5. Assemble the reducing nut;
6. Install the tee (to make bypass and from the discharge reservoir);
7. Assemble an elbow, to make a straight line through the discharge reservoir, figure 4.18.

- **Phase Two**: Experimental Tests

After phase one (assembly) it was necessary to check the system security, and despite of all elements were assembling, it was necessary to check leaks existence. Moreover, to perform this test it was necessary to have the system powered up.

Installation site, in DEE FCT NOVA does not have any 3 phase socket neither any connection point, so an auxiliary switch board was used, assuring protection of people and equipments, figure4.19.

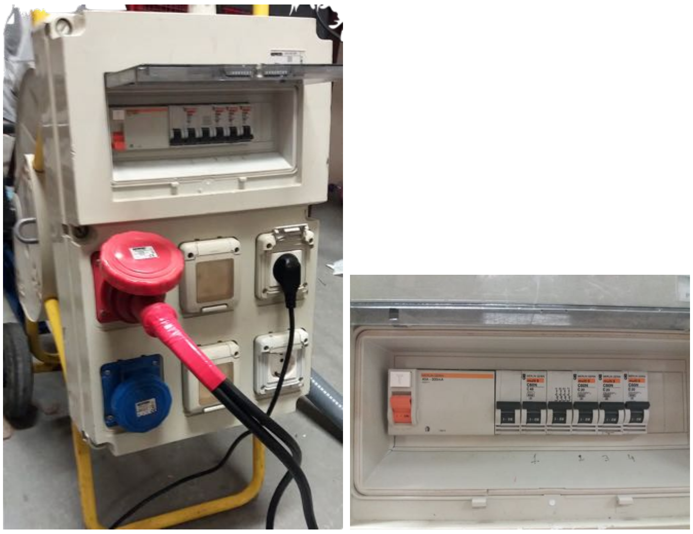


Figure 4.19: Auxiliary Switchboard with interrupters and protection

For leakage tests, first the discharge reservoir needed to be full of water, so around 200 liters were placed inside the discharge reservoir. Then it was necessary to verify that there were no leaks in the system, but to test this situation it was necessary to turn on the initial pump, and put water flow through the pipelines. Moreover, the motor-driven pump can only start after filling the body of the pump and the suction piping with liquid, through the designated hole, red circle in figure 4.13.

A variable three phase autotransformer was used to change the voltage level (between 380-400V) and correspondingly change flow, figure 4.20, the autotransformer was connected to the auxiliary switch board.

The steps for pump electrical connection are:

1. Check the terminal box connection, figure 4.22;

2. Choose the electrical configuration: star-connected system and exchange terminals, in terminal box, figure 4.23;

3. Connect each terminal with the autotransformer, make sure connection between terminal box and terminal cables are well established, 4.20;

4. Increase the voltage level and check if the pump rotation is correct. If not, exchange wires between two phases.

Figure 4.20: Pump Autotransformer

5. Increase voltage level until the maximum value recommended by manufactures and after 5 min switch off the system and check for possible leaks.

If leaks were found phase one (construction) should be repeated in order to avoid system leaks.

However, it was also necessary to prepare the hydropneumatic reservoir, the PAT and the flow meter, before the beginning.

Hydropneumatic reservoir configuration, see figure 4.21:

1. At this point the hydraulic reservoir is empty (no water and no pressure);
2. The insulating valve (02) and bottom purge valve (10) are closed;
3. Close all Level check Valves (1), (2) and (3);
4. Open the discharge valve (5) to drain off all the air, stored in the inside part of hydropneumatic reservoir, this valve must be opened till step number 8;
5. Carry on the first stage of reservoir pre-loading with compressed air through preload valve (6) (Maximum preload 1 bar);
6. Check for air leaks, in case there are any, remove all the compressed air from the reservoir;
7. Slowly open the insulation valve (02), and let discharge valve (5) open in order to drain all air in the branch connection;
8. Close the discharge valve (5) when it only drains water under pressure (no more air in the connection branch);

9. With the insulation valve (02) open, let water enter till the manometer (4) register 2 bar;

10. When pressure in the manometer (4) reaches 2 bar close insulation valve (02) that connects the hydropneumatic reservoir with the network branch.

11. 2nd phase of preload: increase the pressure for the double, if manometer (measure 2 bar, the new value is 4 bar)

12. To finish the process slowly open the section valve (02) to both value water level and pressure stabilized;

13. Tests must be carried on with the pump and PAT stopped;

14. Never open any valve with the pumps switch on, such operation can cause the internal diaphragm damage.

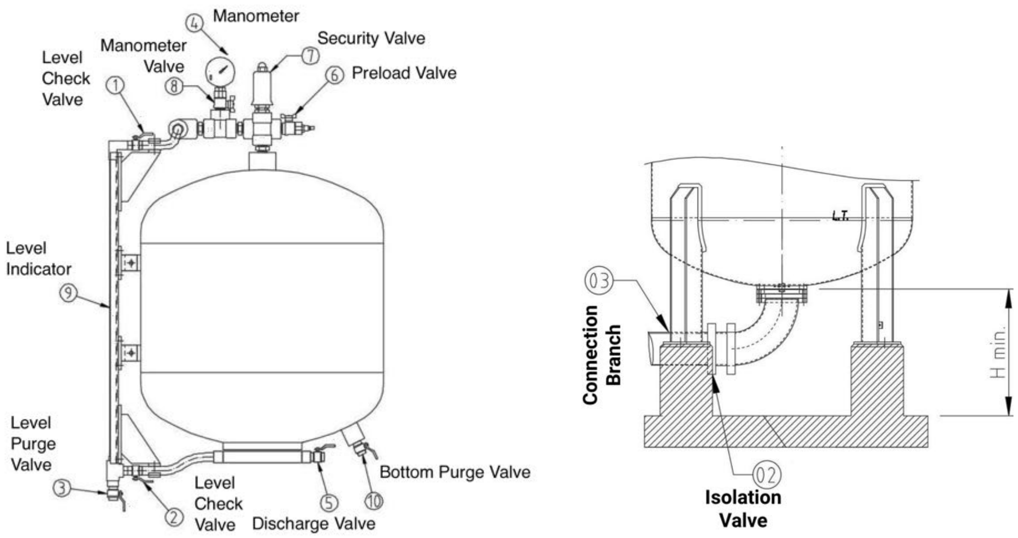


Figure 4.21:
Hydropneumatic Reservoir: Elements description

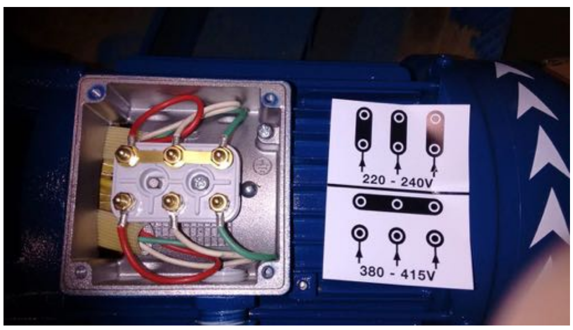


Figure 4.22: Default Pump Terminal Box Connection

Pump as a Turbine Configuration, see figure 4.26:

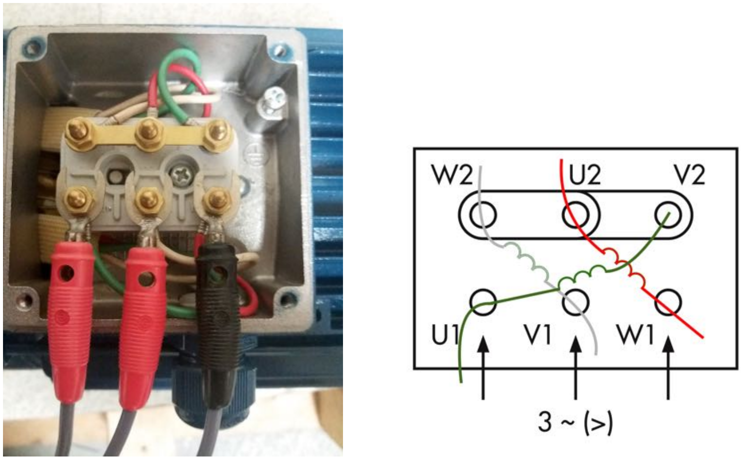


Figure 4.23: *Pump*: Terminal Box and Coils Connection

1. Choose the three phase electrical configuration: star-connected, 3 wired;
2. Confirm the terminal box connections (coils connection), figure 4.25;
3. Connect the terminal wires with the autotransformer number 2, to have a variable voltage in PAT terminals, in order to be possible to invert the power flux, figure 4.24;
4. Connect the crocodile terminals of power analyser, to measure energy flow.

Figure 4.24: Pump as a Turbine Autotransformer

Flow meter and Inductive Sensor configuration:

1. Place the inductive sensor under the flow meter, the inductive sensor must be perfectly aligned with a small hole in the flow meter, to be able to measure a complete rotation of the flow meter (1 rotation = 1 pulse = 10 liters);
2. Verify all Arduino Uno bread board wire connections (water passing through flow meter causes disturbances and some wires can be unpluged), see the detailed schematic presented, figure 4.27;

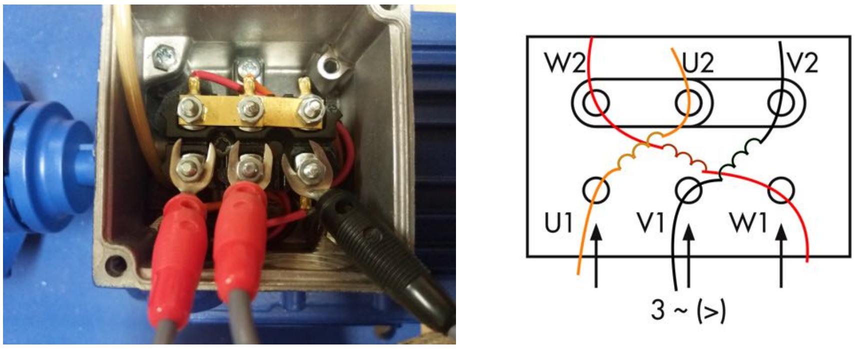


Figure 4.25: *Pump as a Turbine*: Terminal box and coils connection

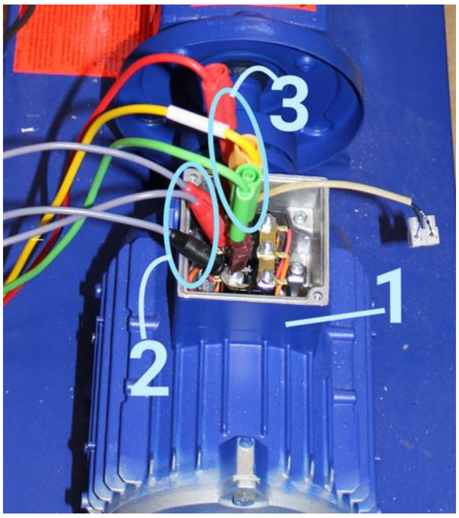


Figure 4.26: *Pump as a turbine*: 1. Terminal box, 2. From autotransformer, 3. To power Analyser

3. Power the Arduino Uno;

4. Upload the code file to Arduino Uno;

After verifying the non-existence of leaks in the system and the configuration of special elements it is possible to start phase two (experimental tests) description:

1. Make Sure the all system is powered off;

2. Open the necessary Ball Valves;

3. Verify if all the pipelines are full of water;

4. Turn on the Arduino Uno;

5. Switch on the differential and three phase interrupters;

6. Slowly increase the voltage level in autotransformer 1;

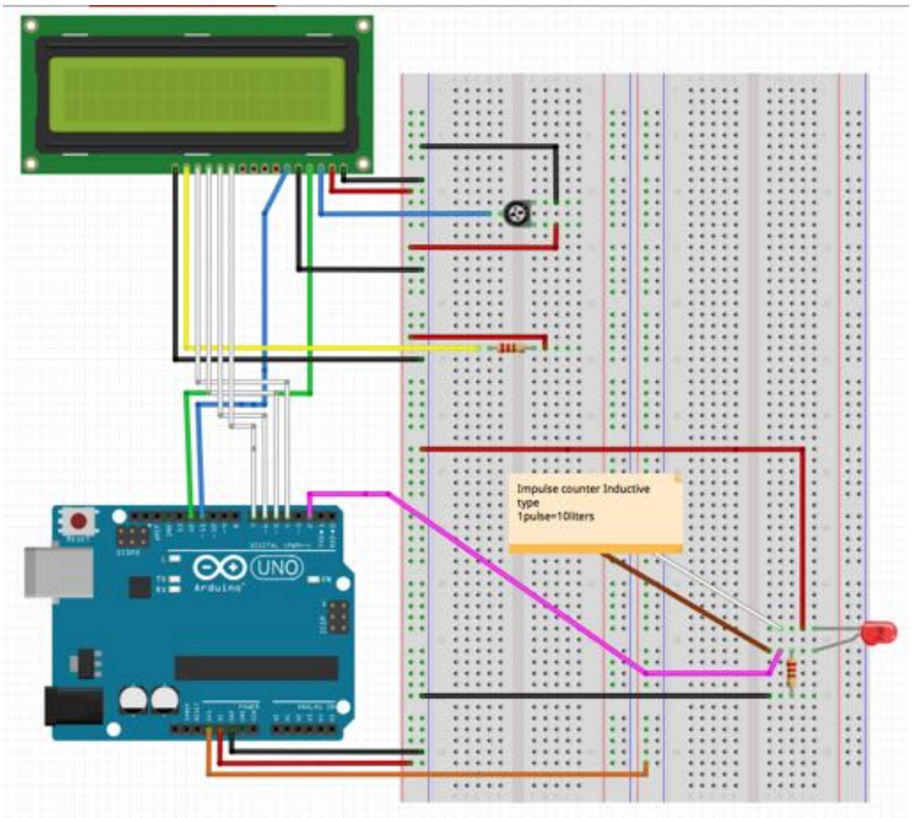


Figure 4.27: Arduino Uno and Inductive Sensor: Connection scheme

7. Start pump starts operation, measurement of voltage and current, use the multimeter and a clamp meter;

8. Slow increase the voltage in autotransformer 2;

9. Turn on the power analyser;

10. Find the point of maximum power;

11. Record the voltage and current values of both machines as well as the flow measured value by Arduino Uno;

12. Increase/decrease voltage in initial pump, to make other tests;

13. Regulate the voltage in Auto transformer 2 to have the maximum value of energy injection in the network.

After these steps the system must be shut down, decrease voltage level in autotransformer 1 and 2. In this point is necessary to have some caution, a suddenly system shut down can cause hydraulic and electric damage.

- Lack of available space in the laboratory: in some situations the available space was not enough to assemble and operate elements correctly and safely (e.g. the initial system position of some valves implied the use of many accessories, increasing also the installation cost);

- Budget Restrictions: initially, the design had a type of pipeline (transparent PVC) that was too expensive and almost unavailable, so it was replaced by PEAD and PVC pipes. The change caused some installation problems, as the new type of pipe was hard to handle and rigid. In some parts of the system it was not possible to keep a straight line because pipes were not flexible enough.

- The design of DN5O fittings was found to be too expensive and was replaced by a small nominal diameter using adaptors. Also the number of fittings was reduced because of space and cost reduction.

After the assembly of system elements the new set up is described in figure 4.28.

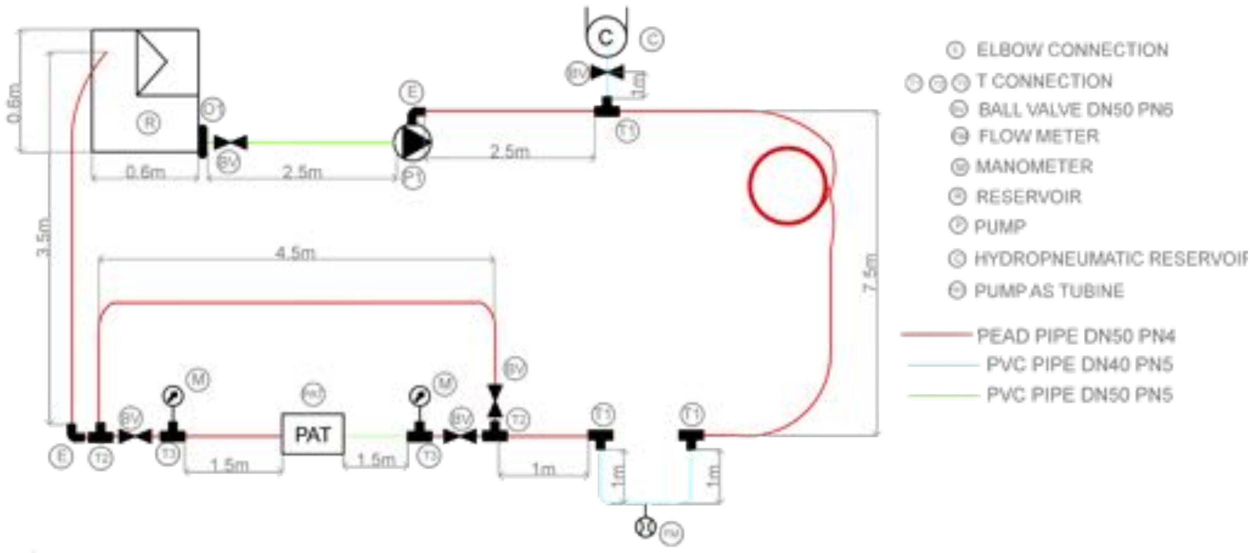


Figure 4.28: Experimental unit (final Setup)

The proposed design system was adjusted as a way to guarantee the maximum efficiency as well as an optimization both in terms of material and implementation methods.

Table 4.7: Total Head loss

Type of loss	Value
Regular	3.6 m
Singular	3.3 m
TOTAL	6.9 m

The initial design suffered some changes, so the new head loss were calculated in order to verify if the initial parameters were still valid, table 4.7, was possible to see that total head losses increased for 6.9 meters.

As mentioned before, a review to the initial design was made, the change does not affect any of the initial specifications for the network elements (e.g. pre-selected PAT and pump), neither the operation point.

In figures 4.29, 4.30 and 4.31 it is possible to see three moments of this system implementation (kick-off, middle state and conclusion).

Figure 4.29: Test rig kick-off

Figure 4.30: Midlle state of the development

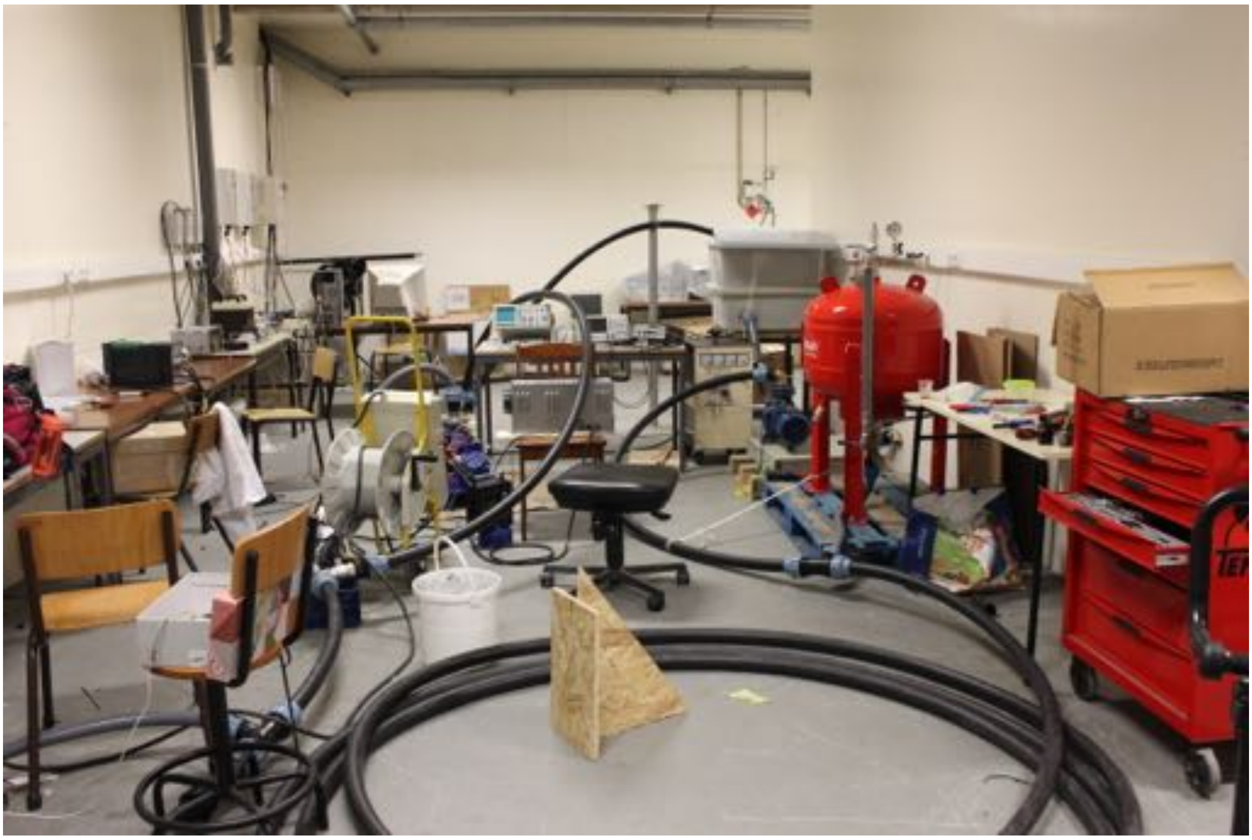


Figure 4.31: Conclusion

Chapter 5

Experimental Results

In this section will be presented the experimental results of this study and their main conclusions.

As mentioned before, the control variables for the experimental tests were voltage levels both at the circulation pump and PAT terminals. Which means that regulating voltage at PAT terminals allows to change consumed and generated power. Its control makes it possible to discover the best efficiency point under the available conditions of flow and pressure.

Such variables of pressure and flow will be considered to be constant over the experimental time, after reaching the steady state. This assumption was made because it was not possible to study the effect of PAT switch on and off in system conditions.

To start, the PAT was used a direct on-grid connection, see figure 5.1, the simplest and cheaper grid connection. This type of grid connection is suitable if the inrush current of the motor does not cause a voltage drop to the main supply. This type of connection is suitable for small hydropower production.

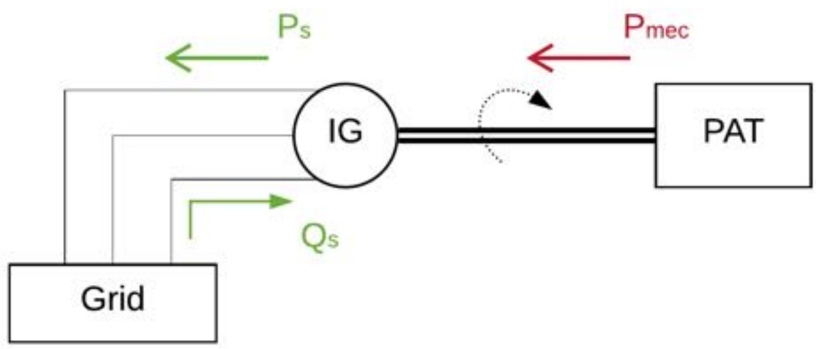


Figure 5.1: PAT: Direct on-grid connection

In this case, lets assume that the system can be described as a 3 phase network. Meaning that the system is only composed by the network (3 phase network) and the load (PAT induction machine). PAT energy production can be explained using Steinmetz scheme, figure 5.2.

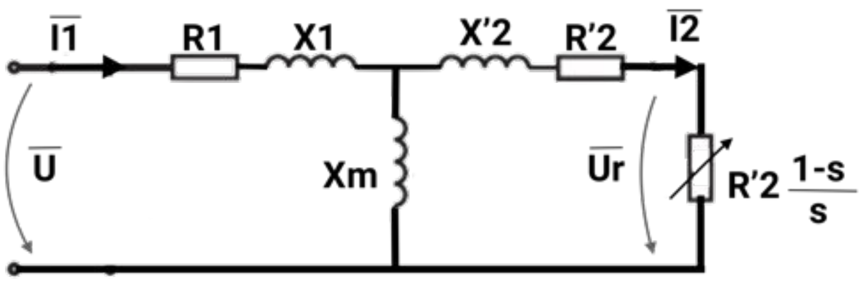


Figure 5.2: Steinmetz scheme per phase

Neglecting magnetization losses and inrush current, the system can be simplified, and figure 5.3 describes the power flow for this machine when operating as a motor.

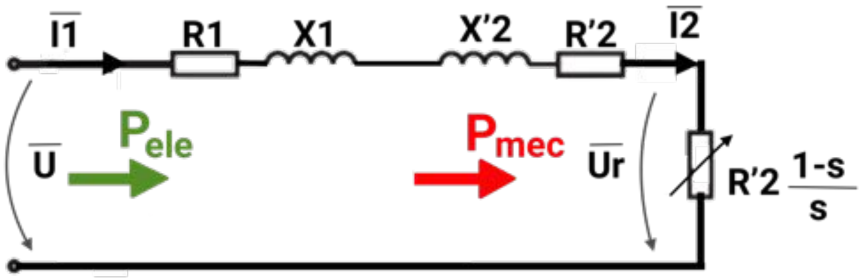


Figure 5.3: Simplified scheme with power flow

From the simplified scheme it is possible to write the equation 5.1 that will be positive when the grid provides energy to the induction machine, classic motor operation. In this case, mechanical power supplied to the shaft is positive $P_{mec} > 0$, and the machine will absorb energy from the network.

$$P_{mec} = 3R_2' \frac{1-s}{s} I^2 \tag{5.1}$$

Where,

P- the mechanical power;

R_2' - load resistance referred to the stator;

s - motor slip;

I^2 - load current.

The operation mode as a motor or generator is dependent on the slip value (positive or negative). Slip is calculated using equation 5.2 where N is the rotor speed and N_s the synchronous speed.

$$s = \frac{N_s - N}{N_s} \tag{5.2}$$

If $N > N_s$, the slip will be negative and the system is no longer operating as a motor, it is operating as a generator. And $P_{mec} < 0$, the load, will inject energy in the network, and the following relation will be negative $P_{ele} = 3U_R I cos(U_R^I) < 0$, the network will absorb energy from the PAT.

To impose the grid frequency to the machine and achieve the synchronous speed it was necessary to use an autotransformer, being the machine working as a motor. After the synchronous speed was exceeded by the rotor, the machine starts to work as a generator and it is able to produce electrical power.

In table 5.1 the obtained results for PAT, working as a generator are presented.

As previously seen, the voltage at circulation pump was controlled between 380 V and 415 V, and several tests were performed to test PAT efficiency.

Table 5.1: Experimental Results for a PAT

		TEST ID		
		#1	**#2**	**#3**
Pump Voltage	***V_PUMP*** **[V]**	380	400	410
Flow	**Q [L/S]**	3.2	3.3	3.4
PAT Voltage	***U_phase*** **[V]**	82.3	94.1	91.1
Current	***I*** **[A]**	1.6	1.7	1.8
Active Power	***P*** **[W]**	-97	-103	-112.4
Reactive Power	***Q*** **[var]**	203.9	251.5	253.9
Apparent Power	***S*** **[VA]**	226.4	272.27	291.4

According to table 5.1, the maximum active power production was P = -112.4 W, for the design flow of 3.4 L/s. The negative signal reflects an inversion of the power flow, active power was injected in the network by the PAT.

Moreover, from the three tests (test ID's #1, #2 and #3) run under a specific voltage applied to the circulation pump terminals, it was possible to obtain a relation between voltage and active power, with different voltages applied to PAT terminals.

Test ID #1, presented in figure 5.4, represents a scenario of steady state (U = 52.1 V), during 300 seconds, with a voltage decrease in a certain period of time (T = 180 s). A decrease in voltage level has an effect in the active power with its increase from approximately -95.2 W to -38.6 W.

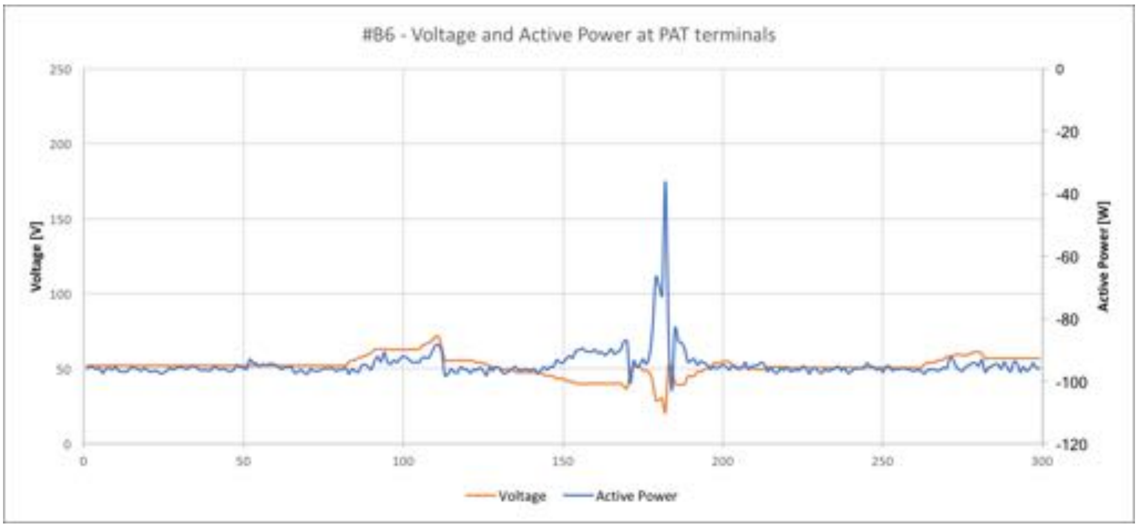


Figure 5.4: Test ID #1: Voltage and active power profile

In this scenario it was only possible to test PAT as a generator with a maximum active power production of -97 W. An active power with a positive signal means that the network is supplying energy; a negative signal means PAT is injecting active power in the network. Table 5.2 presents some relevant points and indicates in each case the machine mode: generator (G) or motor (M).

Table 5.2: Test ID #1: Resume

	1	**2**
U (V)	52.1	21.3
I (A)	1.6	1.2
PF	-0.377	-0.514
ϕ (°)	112.1	120.9
P (W)	-95.2	-38.6
Mode	G	G

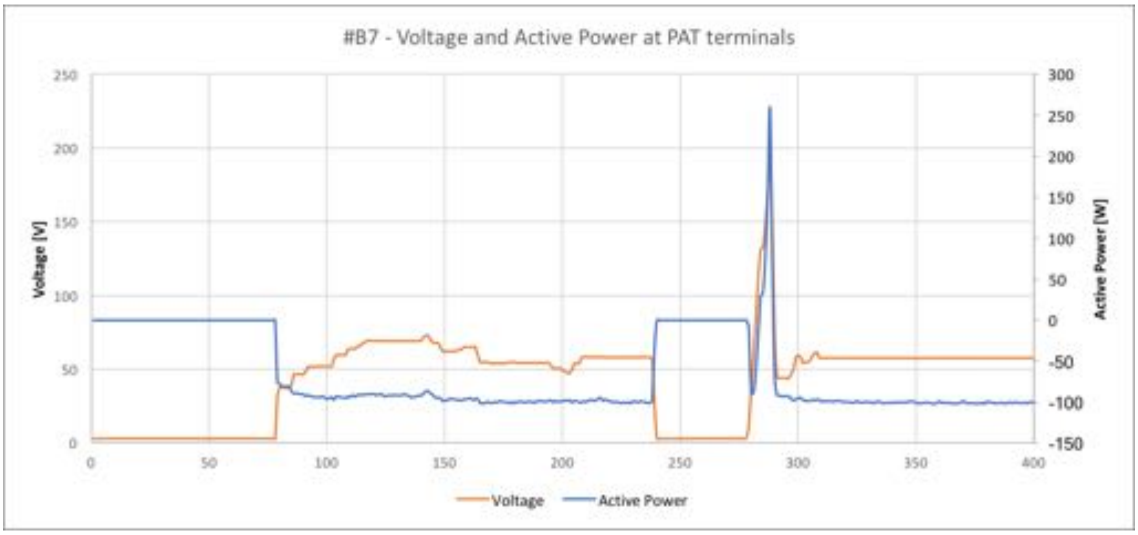


Figure 5.5: Test ID #2: Voltage and active power profile

Figure 5.5 is related to test ID #2 with a duration of T=400 s, with an applied voltage of 400 V to the circulating pump. This is a scenario of sudden voltage increase and decrease, starting from 0 V. Between 0<T<80 both voltage level and active power were zero, which means that PAT has no consumption or production of energy with an applied voltage of 0 V.

When voltage increased to 80 V, there was a decrease in active power which means the machine is working as a generator. However at the peak voltage value of 193.5 V the machine is consuming 339.9 W from the network, thus it is working as a motor.

In table 5.3 it is possible to observe that a decrease in voltage level at PAT terminals will allow the switching to generation operation.

Table 5.3: Test ID #2: Resume

	1	**2**	**3**	**4**
U (V)	193.5	110.7	57.3	26.7
I (A)	5.1	2.7	1.7	0.9
PF	0.112	-0.021	-0.335	-0.481
ϕ (°)	83.6	91.2	109.6	118.8
P (W)	339.9	-18.69	-96.5	-36.2
Mode	M	G	G	G

Pattern scenario simulated in test ID #3 (figure 5.6) was made with an applied voltage of 410 V to the circulation pump terminals. The time duration of this test was T=300 s. While the test ID #2 starts with a voltage equals to zero, in this case the applied voltage to PAT terminals was greater than zero which means that at T=0 s the machine was already working as a generator, at T =24 s a voltage drop occurred and the machine was not producing or consuming energy. At T=155 s the PAT was working as a generator, producing -108.1 W, however in T= 270 s the voltage push up to a maximum of 201.9 V and PAT was working as a motor consuming 420.9 W from the network.

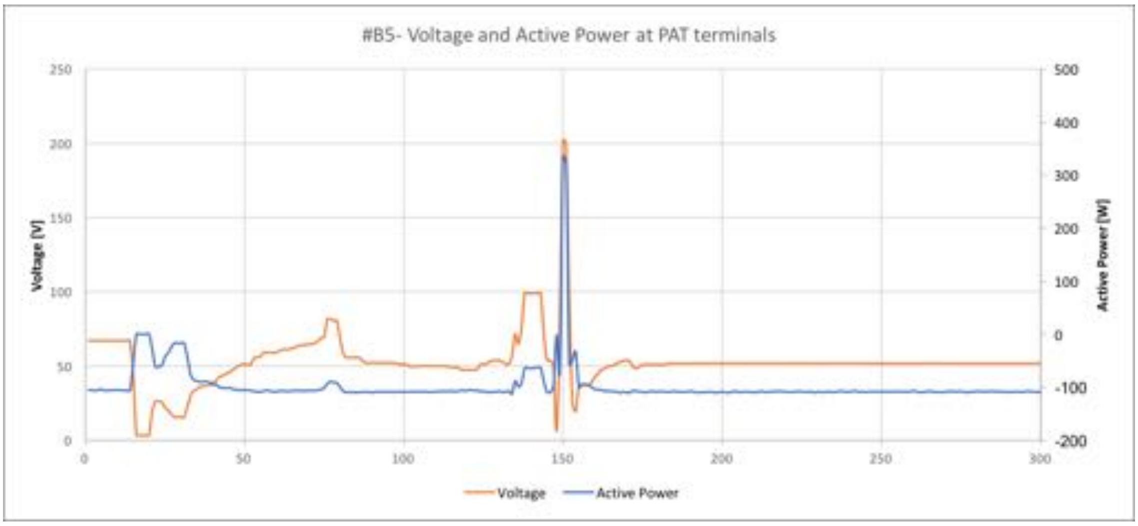


Figure 5.6: Test ID #3: Voltage and Active Power profile

In table 5.4 a resume of the previous scenario can be found.

Table 5.4: Test ID #3: Resume

	1	2	3	4
U (V)	201.9	51.8	22.3	3.7
I (A)	5.8	1.7	1.8	0.115
PF	0.119	-0.414	-0.362	0.321
ϕ (°)	83.2	114.5	111.2	71.3
P (W)	420.9	-108.1	-44.7	0
Mode	M	G	G	-

However, is also possible to determine if the induction machine was operating as a generator or a motor, using voltage and current phasors. If the angle between voltage and current is greater than 90° the machine is working as a generator (figure 5.8), on the other hand, if the angle is below 90° the machine works as a motor (figure 5.7).

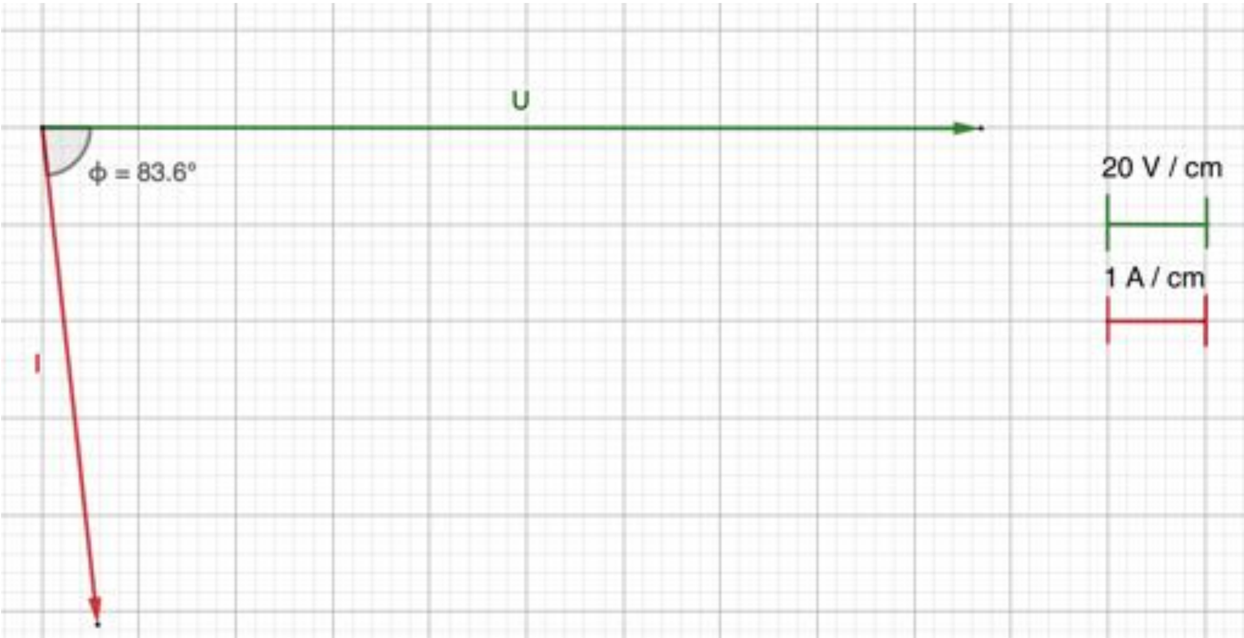


Figure 5.7: Induction machine as a motor (point 2 from test ID #2)

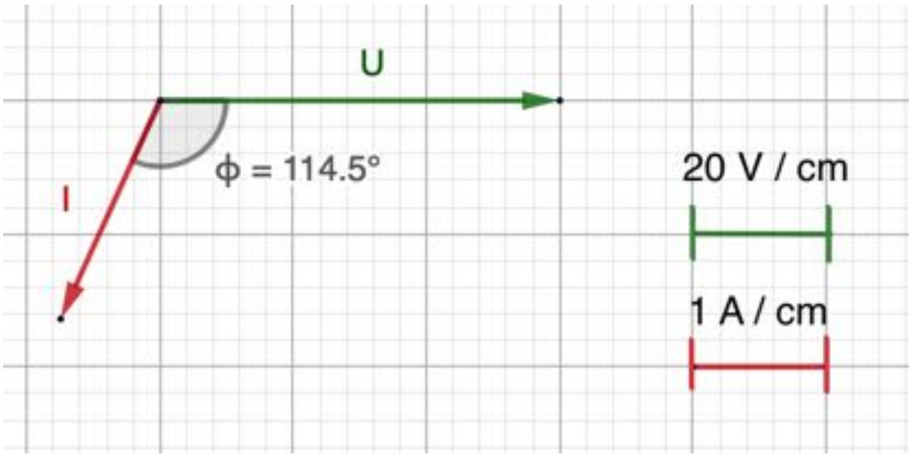


Figure 5.8: Induction machine as a generator (point 1 from test ID #2)

Experimental tests allow to understand the relation between voltage and active power, the voltage increase has a direct impact in active power production or consumption, although in this study the maximum registered value for active power production was -113 W, under steady state conditions of pressure and flow.

When voltage applied to PAT terminals reaches 40 V, it is verified an inversion of active power.

From the voltage increase at PAT terminals it is possible to conclude:

- Current will decrease;
- Power factor decreases, which means the angle between voltage and current increases;
- Active power decreases, the machine starts to operate as a generator.

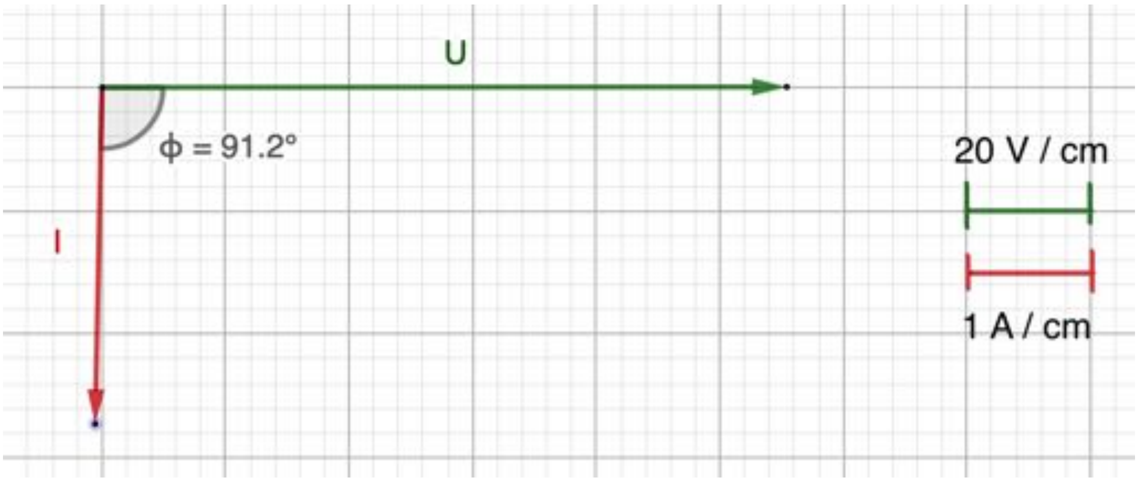


Figure 5.9: Transition between motor and generator operation (point 3 from test ID #2)

Chapter 6

Conclusions

After the conclusion of the research and implementation of this study, main conclusions and future work can be presented. Along with an evaluation of the system performance as an alternative to classic sources for micro energy production.

The main objective of this study was to prove that the use of a pump operating as a turbine can produce and recover energy on a small scale, when introduced into a water distribution network, without compromising the delivery conditions.

Thus, in this study was investigated, through an experimental and simulation method, how to recover energy in water distribution network. It is important to emphasize that these networks are suitable places for the implementation of micro hydro systems, since there is always an available flow (ongoing operation). In addition, all the support infrastructures (pumps, pipes, valves) already exist, reducing installation and implementation costs.

Throughout the development of the thesis, both in terms of literature review and data obtained through the implementation of the test rig, it was evident that it is possible to produce energy by introducing a pump as a turbine into a water distribution network. This conclusion is based on the laboratory experimentation that allowed to identify this technique as a valuable resource in renewable energy production.

In a context of real water distribution networks, PAT's are more feasible, since flow rates are higher than the used in WDN's allowing a greater recovery of energy, in absolute values.

However, the work that was developed has some limitations, therefore future work is needed.

- **Future Work**

The developed work was built from scratch, so the final test rig is made without using automation and control strategies, being all operations controlled manually.

It is recommended as future work to develop an efficient power converter and a control system which is adequate to the characteristics and specifications of the presented system, in order to allow an efficient interconnection with the network.

Moreover, efficiency test of power generation using a PAT must be carried on using a bank of capacitors correctly sized for the operation of an induction generator.

Induction machine in a squirrel cage is not flexible, but due to its price there is a large field of application to explore.

Lastly, must be reinforce the need to continue the work carried on in this research, to provide the development of projects and equipments that could be implemented in real situations with an industrial production contributing to economic development and to allow the reduction of costs associated to water distribution industry.

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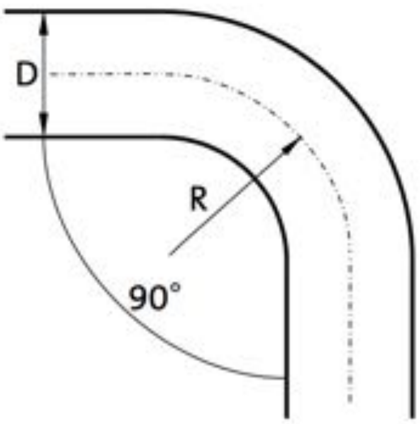
Annex I

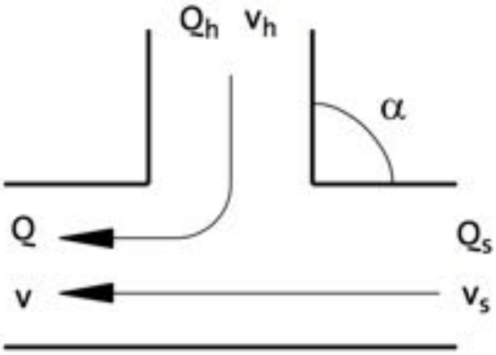
Local Losses Coefficients

Elbow

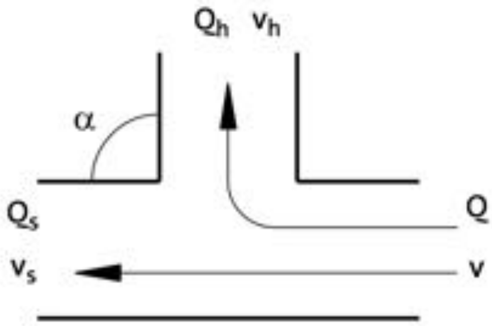


R/D	1	2	3	4	6
ζ	0,36	0,19	0,16	0,15	0,21
R/D	8	10	12	16	20
ζ	0,27	0,32	0,35	0,39	0,41

Tees

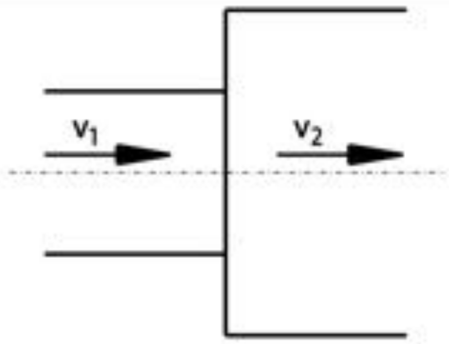


Q_h/Q	Merging flows			
	$\alpha = 90°$		$\alpha = 45°$	
	ζ_h	ζ_s	ζ_h	ζ_s
0,0	-1,00	0,04	-0,90	0,04
0,2	-0,40	0,17	-0,38	0,17
0,4	0,08	0,30	0,00	0,19
0,6	0,47	0,41	0,22	0,09
0,8	0,72	0,51	0,37	-0,17
1,0	0,91	0,60	0,37	-0,54

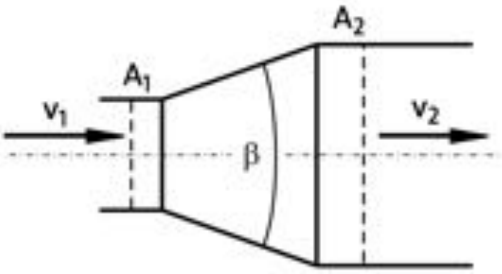


Q_h/Q	Diverging flows			
	$\alpha = 90°$		$\alpha = 45°$	
	ζ_h	ζ_s	ζ_h	ζ_s
0,0	0,95	0,04	0,90	0,04
0,2	0,88	-0,08	0,68	-0,06
0,4	0,89	-0,05	0,50	-0,04
0,6	0,95	0,07	0,38	0,07
0,8	1,10	0,21	0,35	0,20
1,0	1,28	0,35	0,48	0,33

Expansions and Contractions

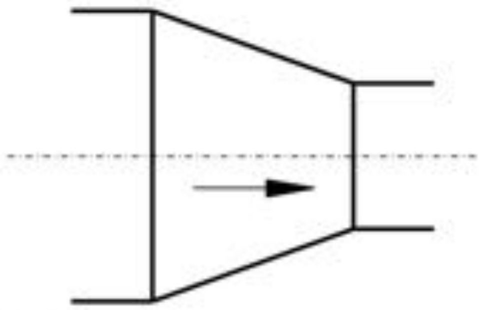


$$H_{Jn} = \frac{(v_1 - v_2)^2}{2g}$$



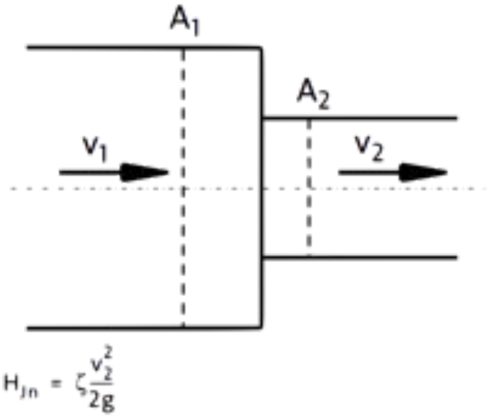
$$H_{Jn} = \zeta \frac{v_1^2}{2g} \qquad \zeta = k\left(1 - \frac{A_1}{A_2}\right)^2$$

β°	k	β°	k	β°	k
5	0,13	45	0,93	100	1,06
10	0,17	50	1,05	120	1,05
15	0,26	60	1,12	140	1,04
20	0,41	70	1,13	160	1,02
30	0,71	80	1,10		
40	0,90	90	1,07		

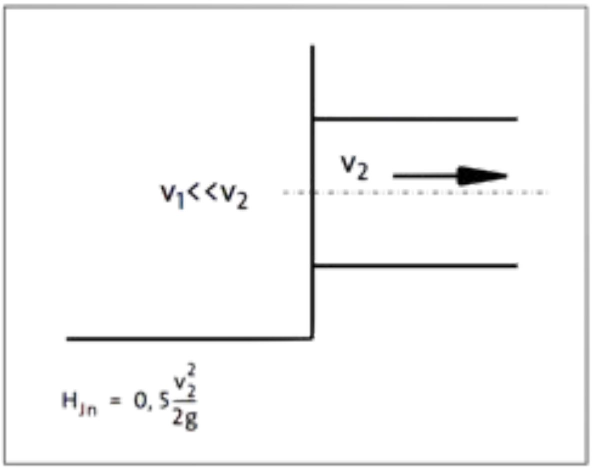


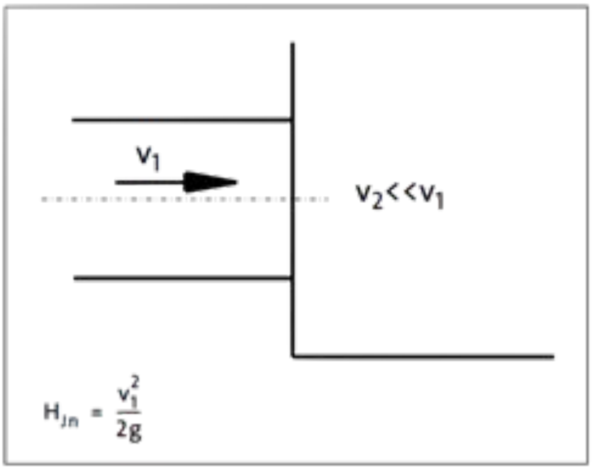
$H_{Jn} = 0$

Friction drag not included



A_2/A_1	0	0,1	0,2	0,3	0,4
ζ_2	0,50	0,46	0,41	0,36	0,30
A_2/A_1	0,5	0,6	0,7	0,8	0,9
ζ_2	0,24	0,18	0,12	0,06	0,02

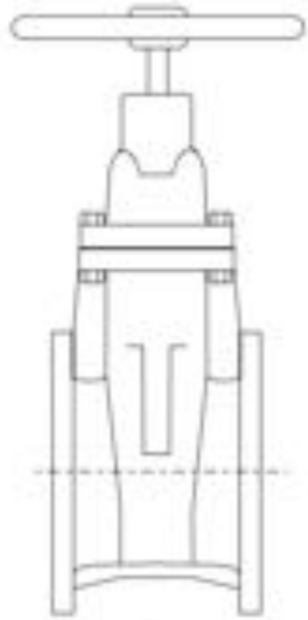




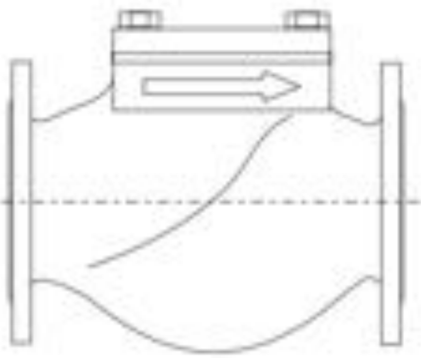
Valves

In valves, ζ value will depend on the the type of valve (butterfly, ball, swing, gate) and for exact information the information must be provided from the manufacturer or supplier.

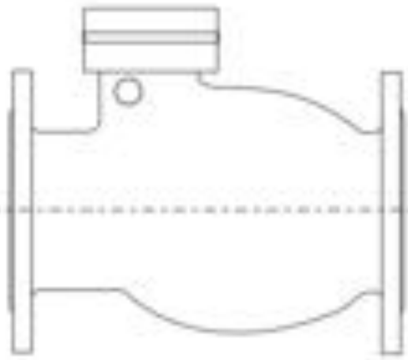
ζ values presented in the previous tables are only valid for fully open valves, when the position is partly open ζ values can increase up to 1.5 to 2 times the original value. In order to be fully open a minimum flow velocity should pass through the valve.



Gate valves without narrowing: $\xi = 0{,}1 \ldots 0{,}3$
Gate valves with narrowing: $\xi = 0{,}3 \ldots 1{,}2$



Ball non-return valves $\xi \approx 1{,}0$ (fully open)



Flap non-return valves $\xi = 0{,}5 \ldots 1{,}0$ (fully open)

Annex II

Unit Conversion Tables

Pressure

	Pascal (=Newton per square metre) Pa, (N/m²)	bar bar	kilopond per square metre kp/m²	meter Water Column mWC	Technical atmosphere at (kp/cm²)	Physical atmosphere atm	pound per square inch psi (lb/in²)	
1 Pa	1	10^{-5}	0.1020	$1.020 \cdot 10^{-4}$	$1.020 \cdot 10^{-5}$	$9.869 \cdot 10^{-4}$	$1.450 \cdot 10^{-4}$	1 Pa
1 bar	10^{5}	1	10197	10.20	1.020	0.9869	14.50	1 bar
1 kp/m²	9.8067	$9.807 \cdot 10^{5}$	1	10^{-3}	10^{-4}	$0.9678 \cdot 10^{-4}$	$1.422 \cdot 10^{-3}$	1 kp/m²
1 mWC	9806.7	0.09807	10^{3}	1	0.1	0.09678	1.422	1 mWC
1 at	98067	0.9807	10^{4}	10	1	0.9678	14.22	1 at
1 atm	101325	1.013	10333	10.33	1.033	1	14.70	1 atm
1 psi	6895	0.06895	703.1	0.7031	0.07031	0.06804	1	1 psi

Flow

	Cubic metre per second m³/s	Cubic metre per hour m³/h	Litre per second 1 l/s	Gallon (UK) per minute UK GPM	Gallon (US) per minute UK GPM	
1 m³/s	1	3600	1000	1320	15651	1 m³/s
1 m³/h	$2.778 \cdot 10^{-4}$	1	0.2778	3.667	4.403	1 m³/h
1 l/s	10^{-3}	3.6	1	13.2	15.85	1 l/s
1 UK GPM	$7.577 \cdot 10^{-5}$	0.02728	0.07577	1	1.201	1 UK GPM
1 US GPM	$6.309 \cdot 10^{-5}$	0.02271	0.06309	0.8327	1	1 US GPM

Temperature

Degrees Celsius	Kelvin	Degrees Fahrenheit
°C	K	°F
0	273.15	32
100	373.15	212
- 17.8	255.35	0

	Δt	Δt	Δt
ΔT, Δt	°C	K	°F
1 °C =	1	1	5/9
1 K =	1	1	5/9
1 °F =	9/5	9/5	1

Annex III

EPANET

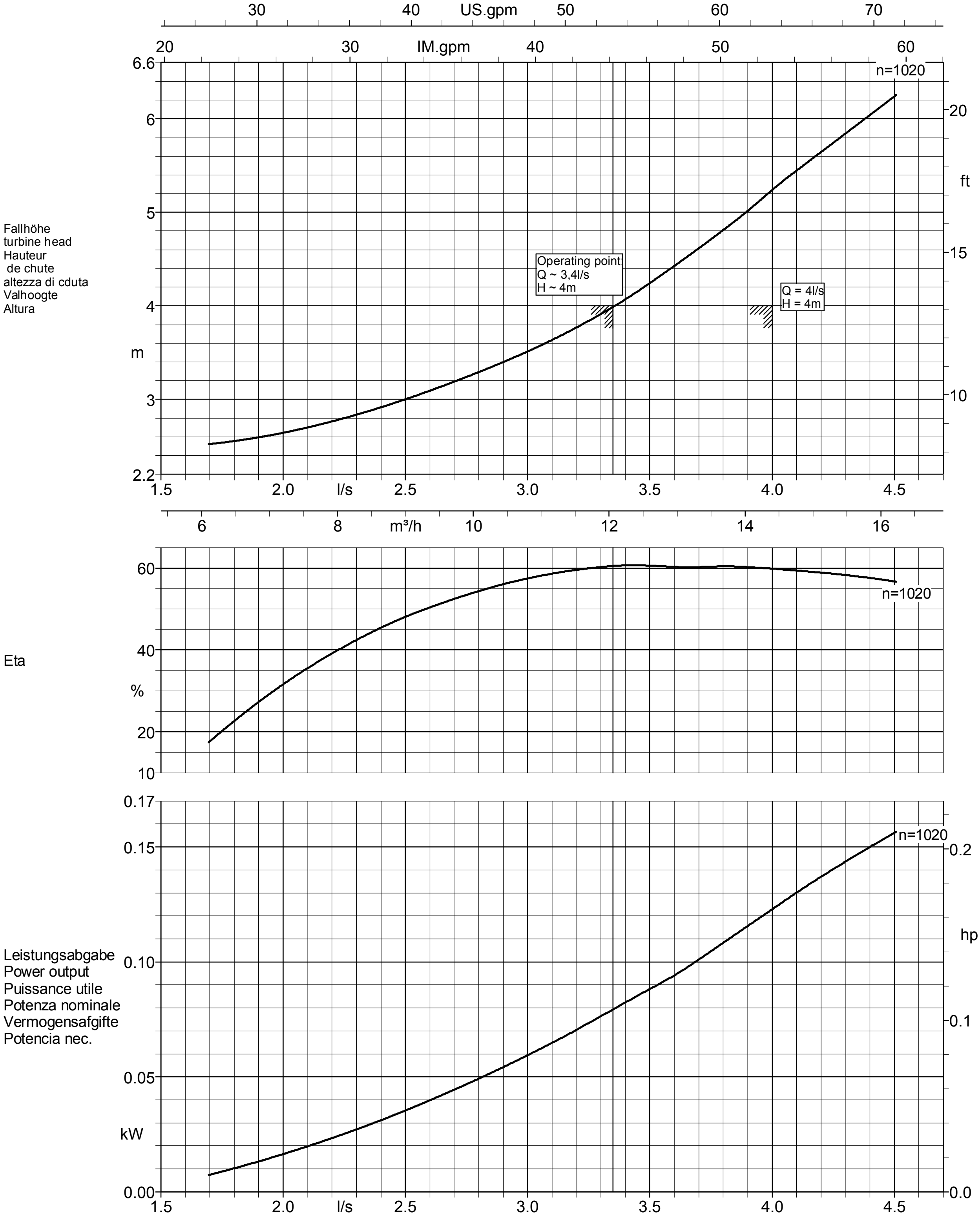
To design the propose system in EPANET, pre-define a system, and after that upload the system in the software.

1. Select a Tank
2. Select Pipes: Specify parameters;
3. Select Nodes: Specify parameters;
4. Insert Pump Curve;
5. Valves: Some of the used valves were not defined, because no special control operation was necessary.
6. Turbine: To simulate this element was used a GPV valve, and then the characteristic curve was load, assuming an Headloss Curve, in this case the PAT curve;
7. Check for errors in report
8. Simulation run successfully;
9. Obtain a graphic of pressure and flow.

ANNEX IV

PAT Data Sheet

Baureihe-Größe / Type-Size / Modèle — Tipo / Serie / Tipo	Nenndrehzahl / Nom. speed / Vitesse nom. — Velocità di rotazione nom. / Nominaal foerental / Revolutiones nom.	Laufrad-Ø / Impeller diameter / Diamètre de roue — Ø Girante / Ø Waaier / Ø Rodete	KSB
Etanorm 32-125 Turbine	1020 1/min	139 mm	
Projekt / Project / Projet — Progetto / Projekt / Proyecto	Angebots-Nr. / Project No. / No. de l'offre — Offerta-No. / Offertenr. / Offerta-No.	Pos.-Nr. / Item No. / No. de pos. — Pos.Nr. / Positienr. / Pos.-Nr.	KSB Aktiengesellschaft 67225 Frankenthal Johann-Klein-Straße 9 67227 Frankenthal
10-01-2432 - Inquiry for IST	2010-01-019		



ρ = 1000.0 kg/m³ T=20.0 °C

Volumenstrom/Flow/Débit/Portata/Capaciteit/Caudal

salaber/2427640/0

Tolerance:
fQ = +/- 9%
fH = +/- 7%
fETA = - 7%

Salamon, Bernhard
T1481
2010-01-29

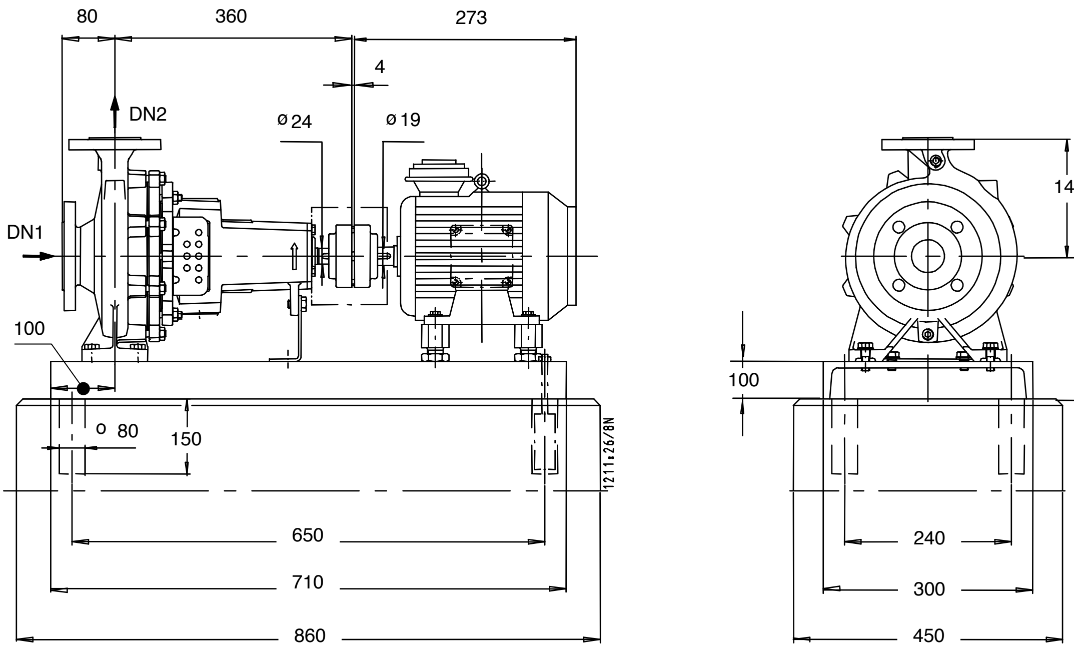
Installation plan

Customer item no.:Lab
Order dated: 12/01/2010
Order no.: 2432 - PaT
Quantity: 1

Number:
Item no.: 400
: 12/01/2010
Page: 1 / 2

Version no.: 1

Etanorm M 032-125 SP
Standardpump acc. EN 733



Drawing is not to scale

Dimensions in mm

Motor

Motor manufacturer	KSB
Motor size	80
Motor power	0.55 kW
Position of terminal box	0°/360° (top)

Baseplate

Design	U-beam / folded plate
Size	13A
Material	Steel ST
Leakage drain, baseplate Rp1	Without
Foundation bolts	M16x250 (Not in scope of supply)

Connections

Suction nominal size DN1	DN 50 / EN 1092-2
Discharge nominal size DN2	DN 32 / EN 1092-2
Nominal pressure suct.	PN 16
Rated pressure disch.	PN 16

Coupling

Coupling manufacturer	Flender
Coupling type	Eupex N
Coupling size	68
Spacer	0.0 mm

Weight net

Pump	34 kg
Baseplate	33 kg
Coupling	1 kg
Coupling guard	2 kg
Motor	9 kg
Total	79 kg

Connect pipes without stress or strain!

Dimensional tolerances for shaft axis height:	DIN 747
Dimensions without tolerances, middle tolerances to:	ISO 2768-m
Connection dimensions for pumps:	EN735
Dimensions without tolerances - welded parts:	ISO 13920-B
Dimensions without tolerances - gray cast iron parts:	ISO 8062-CT9

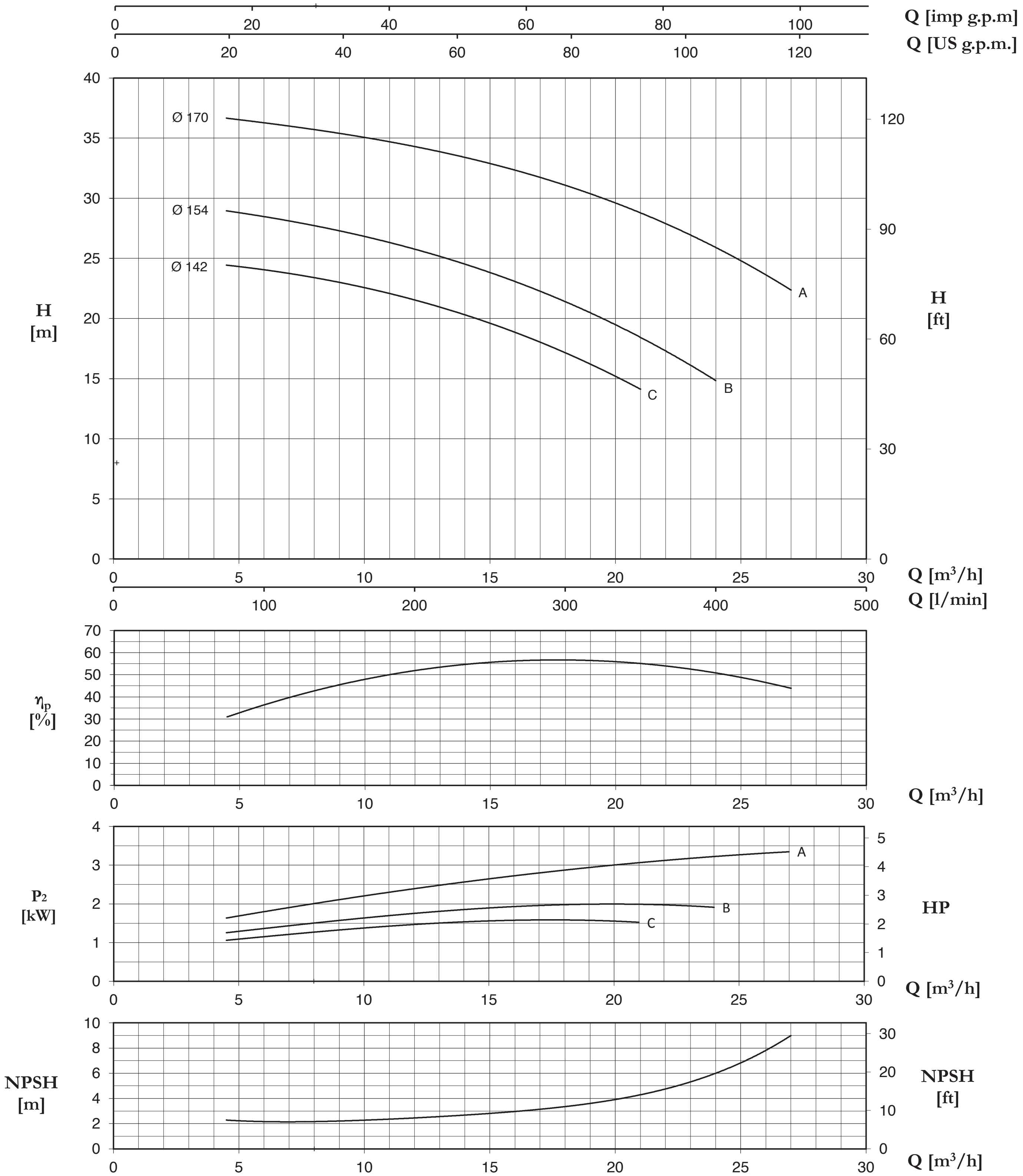
For auxiliary connections see separate drawing.

Annex V

Pump Data Sheet

CM EN 733 ~ 2900 r.p.m.

32-160



TYPE	P2		P1 (kW)	A	Q (m³/h - l/min)										
3~				3~	0	4.5	6	7.5	9	12	15	18	21	24	27
					0	75	100	125	150	200	250	300	350	400	450
	(HP)	(kW)	3~	3x400 V 50 Hz	H (m)										
32-160 C (*)	2	1,5	2,3	4	24,7	24,4	24,1	23,6	23,0	21,5	19,6	17,2	14,1	-	-
32-160 B (*)	3	2,2	2,9	5,2	29,0	-	28,5	28,0	27,3	25,7	23,8	21,4	18,5	14,8	-
32-160 A	4	3	4,1	7,1	36,8	-	36,4	36,0	35,4	34,2	32,8	31,1	28,8	26,0	22,3

(*) Disponibile nella versione monofase / *Single phase available* / Bajo pedido tambien en monofase / *Disponible en monophasé*

Annex VI

Induction Machine Data Sheet

KSB

Customer item no.:
Communication dated: 28/10/2016
Doc. no.: 5594 UNL
Quantity: 1

Number: 4002894771
Item no.:200
Date: 02/11/2016

ETN 050-032-125 GGXAA11GD200056B

Version no.: 2

Pump as turbine (PaT)

SIEMENS

Data sheet for three-phase Squirrel-Cage-Motors

MLFB-Ordering data : 1LA7083-6AA10-Z
X88

without (standard)

Client order no. :
Order no. :
Offer no. :
Remarks :

Item no. :
Consignment no. :
Project :

Electrical data:

Rated voltage :	(1) 230 VD/400 VY, 50 Hz, 460 VY, 60 Hz					
Frequency :	50 Hz			60 Hz		
Rated power :	0.55 kW			0.63 kW		
Rated speed :	910 1/ min			1110 1/ min		
Rated torque :	5.8 Nm			5.4 Nm		
Rated current (IE) :	VD 2.78 A	VY 1.60 A			VY 1.60 A	
Starting / rated current :	3.4			3.7		
Breakdown / rated torque :	2.2			2.2		
Starting / rated torque :	2.1			2.1		
	4/4	3/4	2/4	4/4	3/4	2/4
Efficiency %	67.5%	67.0%	63.5%	67.5%	67.0%	63.5%
Power factor :	0.74	0.68	0.55	0.73	0.67	0.54
Efficiency class :	-/-			-/-		

Mechanical data:

Sound pressure level 50Hz/60Hz (load) :	40 dB(A)	44 dB(A)
Moment of inertia :	0.0017 kg*m²	
Bearing DE :	6004 2ZC3	
Bearing NDE :	6004 2ZC3	
Type of bearing :	Floating bearings pre-loaded DE (standard)	
Condensate drainage holes :	No	
Regreasing device :	No	
Lubricants :	Esso Unirex N3	
Grease lifetime/Relubrication interval :	40000 h	
Quantity of grease for relubrication :	null g	
External earthing terminal :	No	
Coating :	Special paint finish RAL 7030 stone gray	

Environmental conditions:

Ambient temperature :	-20 °C - +40 °C
Altitude above sea level :	1000 m
Standards and specifications :	IEC, DIN, ISO, VDE, EN

General data:

Frame size	080 M
Design of rotating electrical machines :	(0) IM B3 / B6 / B7 / B8 / V5 without canopy
Weight in kg, without optional accessories :	10.00 kg
Frame material :	Aluminum
Degree of protection :	IP 55
Method of cooling, TEFC :	IC 411
Vibration class :	A (Standard)
Insulation :	155(F) to 130(B)
Duty type :	S1 - continuous duty
Direction of rotation :	Bi-directional

Terminal box:

Material of terminal box :	Aluminum
Type of terminal box :	gk 030
Contact screw thread :	M4
Max. cross-sectional area :	1.50 mm²
Cable diameter from ... to ... :	9.00 mm - 17.00 mm
Cable entry :	1xM25x1,5-1xM16x1,5
Cable gland :	2 plugs

Special design:

X88 KSB specific execution

Technical data are subject to change! There may be discrepancies between calculated and rating plate values.

Generated: 09.12.2016 16:46:58

Driver datasheet online

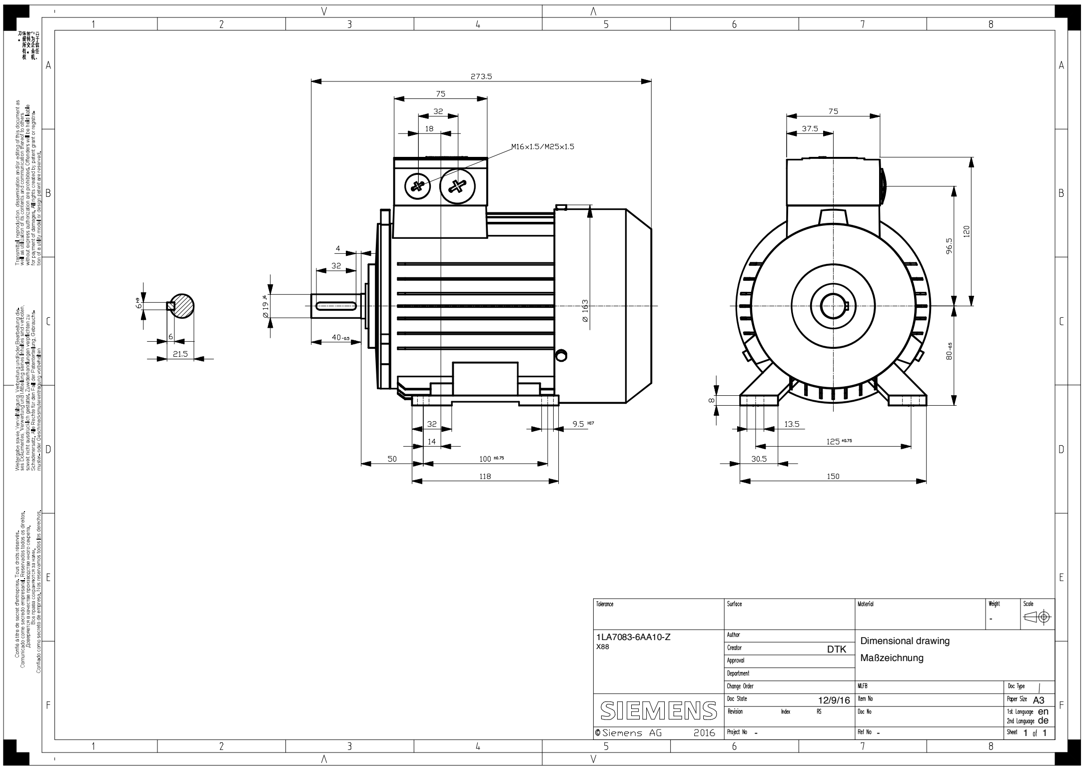
Customer item no.:
Communication dated: 28/10/2016
Doc. no.: 5594 UNL
Quantity: 1

Number: 4002894771
Item no.:200
Date: 02/11/2016
Page: 2 / 3

ETN 050-032-125 GGXAA11GD200056B

Version no.: 2

Pump as turbine (PaT)



Annex VII

Arduino Uno Code: Flow Meter

Listing VII.1: Hello World

```
#include <LiquidCrystal.h>

//constant
const int flowPin = 2;    //This is the input pin on the Arduino

//variables that change value
double flowRate;   //This is the value to calculate.
volatile int pulse_count;


int i=0;
int pulsoAnterior=1;
unsigned long elaps, auxtime1;
unsigned long time1=0, time2;
unsigned long t1=0,t2=0,aux=0, tempoInicial=0, tempoActual=0,
 tempoTotal_seg=0, tempoTotal_milis=0;
double caudal;
double fluxo=0;
unsigned long teste;

// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(12, 11, 7, 6, 5, 4);

void setup() {
  // put your setup code here, to run once:
  pinMode(flowPin, INPUT_PULLUP);           //Sets the pin as an input
  attachInterrupt(0, Flow, FALLING);
  //Configures interrupt 0 (pin 2 on the Arduino Uno) to run the function "Flow"
  Serial.begin(9600); //Start serial: Baud     the default speed
```

```


  //LCD Configuration
  lcd.begin(16, 2);
  lcd.print("FLOW␣METER");
  delay(1000);
  lcd.clear();


  //time setup
  tempoInicial= millis();
  pulse_count=0;
  t2=t1=millis();

}
void loop() {
  // put your main code here, to run repeatedly:

  interrupts();   //Enables interrupts on the Arduino
  delay (1000);   //Wait 1 second
  noInterrupts(); //Disable the interrupts on the Arduino

  int valueOfPulse = digitalRead(flowPin);



    int contador=pulse_count;
    int tempoTotal_seg = tempoTotal_milis/1000; //para colocar em segundos

    fluxo= (contador*10); //1 pulso =10Litrs CONTADOR JANZ Q3 JV400
    fluxo=fluxo/(tempoTotal_seg);
    fluxo=fluxo/0.01667; //conversor para L/MIN
    Serial.print(fluxo);
    Serial.println("L/MIN");
    Serial.print("Pulses:");
    Serial.println(contador);
    Serial.print("Time:");
    Serial.print(tempoTotal_seg);
    Serial.println("␣s");
    Serial.println("\n");

//LCD PRINT
    lcd.setCursor(4,0);
    lcd.print(fluxo);
    lcd.print("L/MIN");
    lcd.setCursor(4,1);
    lcd.print(contador);
    lcd.print("pulsos");

}
```

```
void Flow()
{
   pulse_count++; //Every time this function is called, increment "count" by 1

    t1=t2;
    t2=millis();

    aux=t2-t1;
    tempoTotal_milis= tempoTotal_milis+aux;

}
```

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